TD-98-052

HGQ-03 Production Report

by

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1.0 Introduction

This report summarizes the production history of the third 2-meter long model magnet, HGQ-03. These model magnets are part of the US LHC program in which the FERMILAB has to fabricate and test 20 IR quadropoles for CERN. The baseline design is described in the HGQ Conceptual Design Handbook. HGQ-03 is the first magnet with internal splice design as opposed to an external splice design for both HGQ-01 and HGQ-02. The internal splice is made within the radial space which contains the outer coil whereas the external splice is made outside the coil perimeter. The objective of this magnet was to compare the two splice designs and also to improve the overall magnet quench performance.

Magnet #	Strand/ Cable	Magnet Design	Mechanical Design	Thermal Design	Quench Protection
HGQ02	SSC strands. Original cable design / X-section (1.0).	Basic cross-section Modified ends.	ULTEM end parts. External Splice / Al end can on LE and Full SS Round Collars in RE	Kapton Insulation (100 μm). <u>Inner cable:</u> 1 layer of bare .001 x .375 in Kapton with 50% overlap surrounded by 1 layer of .002 x .375 in Kapton with 2 mm gaps and with polyimide adhesive. <u>Outer cable:</u> 1 layer of bare .001 x .375 in Kapton with 50% overlap surrounded by 1 layer of .002 x .375 in Kapton butt lapped with polyimide adhesive.	Interlayer & Outer layer quench heaters. Spot heaters
HGQ03	SSC strands. Original cable design / X-section (1.0).	Basic cross-section Modified ends.	ULTEM end parts with ***QIX sheet adhesive***. ***Internal Splice/round SS collars on both ends.*** ***No end loading.*** ***Anchor CM with two tabs.*** ***LE with Collet yoke pack and no RE yoke pack.***	***Variation of cable insulation thickness for inner cable (127μm)*** <u>Inner cable:</u> 1 layer of bare .001 x .375 in Kapton with ***54% overlap*** surrounded by 1 layer of .002 x .375 in Kapton with 2 mm gaps and with polyimide adhesive. <u>Outer cable:</u> 1 layer of bare .001 x .375 in Kapton with 50% overlap surrounded by 1 layer of .002 x .375 in Kapton butt lapped with polyimide adhesive.	***Optimized quench heaters*** (with copper) Interlayer & ***Outer layer double element (by LBNL)*** quench heaters. Spot heaters

Table 1: *Comparison between HGQ-02 and HGQ-03*

A mechanical plan detailing all the fabrication steps and the corresponding design issues was proposed before the production to give enough notice for all the responsible engineers. The following table summaries the plan:

D. Chichili / F. Nobrega

PROCESS	DESIGN ISSUES	PARAMETERS	STATUS
Cable Preform	Outer cable turn-around Inner cable turn-around Inner cable ramp Splice Geometry	Tooling Modifications	Trial runs have been carried out and the procedure has been developed
Cable Insulation	Thickness	For Inner cable: 54% overlap of the inner wrap ➔ total kapton insulation = 127 μm.	One Inner R&D coil was made. Increase in coil size=7 mil
Coil Winding + Curing + Measuring	Curing cycle End-parts Coil size and modulus	-190 ^{0}C – 200 ^{0}C with QIX sheet adhesive between the end-parts and the cable. -Increse the end-loading from 1500 Psi to 2500 Psi. -End-parts wiped with Isopropyl alcohol.	Adhesive R&D showed that bond strength increases by a factor of 1.5 with QIX sheet adhesive.
Coil Assembly	Voltage tap configuration End-compression Spot heaters Interlayer / Outer layer QH Ground insulation	-see MD-344883 and MD-344884 (Rev. A) -End-part sizing upto 83 MPa pressure was done only once after the voltage taps are installed. -Number + Location -Interlayer same as HGQ-02 and LBNL heaters on outer layers	See pg. 15 Layer of 5 mil kapton sheet was removed to put LBNL heaters.
Collaring	Targeted coil prestress Expected collar-coil deflection Strain gauge locations Special collars	-83 MPa (for both Inner and Outer coil) -From HGQ-01 and HGQ-02 -Locations at which the coil size was lowest and highest. -Collars with strain gauges	Complete
Yoke and Skinning	Yoke lead end configuration Yoke return end configuration Skin alignment key Skin strain gauges Weld operation specs. Tuning shims	Glued Vs Welded Glued Vs Welded Size of the key Same as HGQ02 or TBD Same as HGQ02	Collet yoke pack was used No RE yoke 24 mm
End-Plate Installation	Weld operation specs. Bullets assembly	End Bullet load (< 6000 lbs)	No end loading
Quadrant Assembly + Soldering	Assembly procedure Soldering Specifications	Same as HGQ-02	Complete
Testing in IB3	Warm measurements		

Table 2: *HGQ-03 Mechanical Plan*

2.0 Pre-Production R&D

HGQ-03 being the first internal splice magnet, it was deemed necessary to check all the new tooling especially the preform fixtures. Further considering the quality of the coils used in HGQ-02, this time was also spent on improving the coil structural rigidity. Hence R&D coils were wound to test the end-part adhesion, coil size, preform fixtures for internal splice and the new curing fixture mold.

The first four weeks were spent on tooling modifications which allowed us to make the ramp-up and turn-around for inner coils and turn-around for outer coils within the internal splice configuration. The ramp-up fixture needed to be modified so that there were no popped strands at the entry and exit of the cable into the fixture. Two long fingers were attached on either side of the fixture to prevent this. Furthermore due to the small radius in the turn-around, there was a concern that we might damage strands during this process. The turn-around areas for both inner and outer coils were etched to resolve this issue. The earlier samples showed some damage to the filaments, but once the procedure was finalized, the samples showed no damage. Travelers were written with this procedure and were followed for the rest of the coils.

The end-parts were wiped with a solvent (isopropyl alcohol) before painting QIX to improve wettability and adhesion. A 1 mil thick QIX sheet adhesive was also placed between the end-parts and the cable while winding to further improve the bonding. See the technical notes TD-98-004 and TD-98-031 for more details on adhesive R&D. For the inner coil, the thickness of the kapton insulation was increased from 50% to 54% (0.03 inch land) overlap of the inner wrap. The reason for doing this was that the inner coils for HGQ-02 were about 275 μm below the nominal size and adding the extra insulation would reduce the amount of shimming during the coil assembly (the nominal size for the inner coils is 375 μm over the master). Further the closed cavity pressure during curing would increase. This may also improve the bonding between the end-parts and the cable. The flip-side of it is that the end-part deformities might be higher. The first R&D inner coil (HGQi-019) was wound with a left lay cable (Reel # 614). It was cured at 190 ^{o}C for 20 mins. The end-part adhesion was much better than any of the previous coils and the coil size jumped from -100 μm to 40 μm over the master (a gain of about 140 μm or 5 - 6 mils). Also the coil modulus increased from 4 GPa to 8 GPa. Note that we were still 125 μm (5 mils) under the nominal size, but we decided to go ahead with this size for HGQ-03 and shim the coils accordingly.

The outer R&D coil, HGQo-015 (Reel # 623) was also wound with a 1 mil thick QIX sheet adhesive between the end-parts and the cable. Further the Ultem spacer on the RE was modified such that the wedges were extended beyond the transition area. This modification was made to allow the wedges to bridge the transition area, making the transition between the straight section and the end area less severe. This might also have decreased any eccentric loading on the end-spacers which would offset their position (HGQ-02 outer coils had this problem). Also the winding tension was decreased from 80 lbs to 70 lbs. For the outer coils, we also increased the curing cavity size by 125 μm (5 mils) in order to reach the nominal size. The end-part adhesion was very good and no rotation in the end parts was observed. Also HGQo-015 has a straight section size of 280 μm over the master at 83 MPa and modulus of 11 GPa. The nominal size is 250 μm over the master. So for outer coils we have reached the nominal size with this configuration.

3.0 Superconducting Cables

3.1 Cable Parameters

The following table lists the main cable parameters:

PARAMETER	UNIT	INNER CABLE BY DESIGN	INNER CABLE FOR HGQ-03	OUTER CABLE BY DESIGN	OUTER CABLE FOR HGQ-03
Radial width, bare	mm	15.4 +/- 0.025	15.3975	15.4 +/- 0.025	15.4050
Minor edge, bare	mm	1.326		1.054	
Major edge, bare	mm	1.587		1.238	
Midthickness, bare	mm	1.457 +/- 0.006	1.4559	1.146 +/- .006	1.146
Keystone angle,	deg	0.99 +/- 0.1	1.048	0.68 +/- 0.1	0.703
Cable packing factor		0.91		0.91	
Number of strands		38	38	46	46
Strand diameter	mm	0.808		0.648	
Pitch direction		right	right	left	left
Pitch length	mm	114		101.6	

Table 3: *Cable parameters as provided by LBNL.*

The cables were cleaned before insulation with Axarel 6100 in the SSC cleaning module.

3.2 Cable and Wedge Insulation

The following table summarizes the cable insulation parameters.

PARAMETER	INNER CABLE	OUTER CABLE
Number of wraps	2	2
Inner wrap:		
-material	Kapton tape 25 μm × 9.5 mm	Kapton tape 25 μm×9.5 mm
-adhesive	None	None
-wrap structure	Spiral wrap with 54% overlap	Spiral wrap with 50% overlap
-thickness	50 μm	50 μm
Outer wrap:		
-material	Kapton tape 50 μm ×9.5 mm	Kapton tape 50 μm × 9.5 mm
-adhesive	Liquid polyimide (“QI” modified)	Liquid polyimide (“QI” modified)
-wrap structure	Spiral wrap with 2 mm gap	Spiral wrap without gap
-thickness	50 μm	50 μm

Table 4: *HGQ-03 cable insulation parameters.*

The wedges were insulated identical to their respective coils.

4.0 Coil Fabrication

The first inner coil, HGQi-021 was wound, cured and measured. Note that the procedure was identical to the R&D coil HGQi-019, expect that this coil was made with a right lay cable. In spite of the increase in insulation thickness, there was no increase in coil size. Compare the coil size data in the following table between the HGQ-02 coils and HGQi-021. It was later discovered that the cavity size for the new curing mold was 20 mils under compared to that used for external splice. The reason why there was an increase in the coil size between HGQi-013 and the R&D coil HGQi-019, in spite of the fact that the cavity size is lower was due to change in outer layer insulation width. The outer wrap of insulation for HGQi-013 was .002 x .188 in with 2 mm gap whereas for HGQi-019 it was .002 x .375 in with 2 mm gap. Hence the number of gaps was reduced by half which leads to increase to size of the coil. See TD-98-043 by R. Bossert for more details. To continue with the HGQ-03 coil fabrication, we decided to increase the cavity size to + 20 mils to match that of the external splice mold. Note that for outer coils, the cavity size was + 5 mils as done for the R&D coil.

COIL#	COIL DESIGN	BODY SIZE / MODULUS	CABLE DIMENSIONS	CAVITY SIZE
HGQi-009 and HGQi-013	Left Lay Cable External Splice Old Curing Mold 50% Overlap	-130 μm, 4.1 GPa and -100 μm, 4.0 GPa	1.4559 mm 1.048^0	+ 20 mils
<u>HGQi-019</u> (R&D Coil)	Left Lay Cable Internal Splice New Curing Mold 54% Overlap	42.7 μm 8.0 GPa	1.4559 mm 1.048^0	0.00
HGQ-02 (HGQi-015 through HGQi-018)	Right Lay Cable External Splice Old Curing Mold 50% Overlap	80 to 120 μm 4.5 GPa	1.4573 mm 1.038^0	+ 20 mils
<u>HGQi-021</u>	Right Lay Cable Internal Splice New Curing Mold 54% Overlap	83 μm 8.2 GPa	1.4573 mm 1.038^0	0.00

Table 5: *Comparison between the R&D coil, HGQi-019 and the first inner coil, HGQi-021. Also shown are the parameters for HGQ-02 coils.*

4.1 Winding and Curing

Five inner and five outer coils were wound, cured and measured for HGQ-03. The winding tension for these coils was 70 lbs compared to 80 lbs for HGQ-02 coils. A QIX sheet adhesive was placed during winding between all the end-parts and the cable. The cavity sizes for the curing mold are +20 mils with respect to the nominal size for inner coils and + 5 mils for outer coils. The curing cycle is identical for both inner and outer coils. The temperature and pressure regimes are same as in HGQ-02 except that the end pressure was increased from 1500 Psi to 2500 Psi. The loading scheme is shown below *[taken from HGQ-02 production report]*:

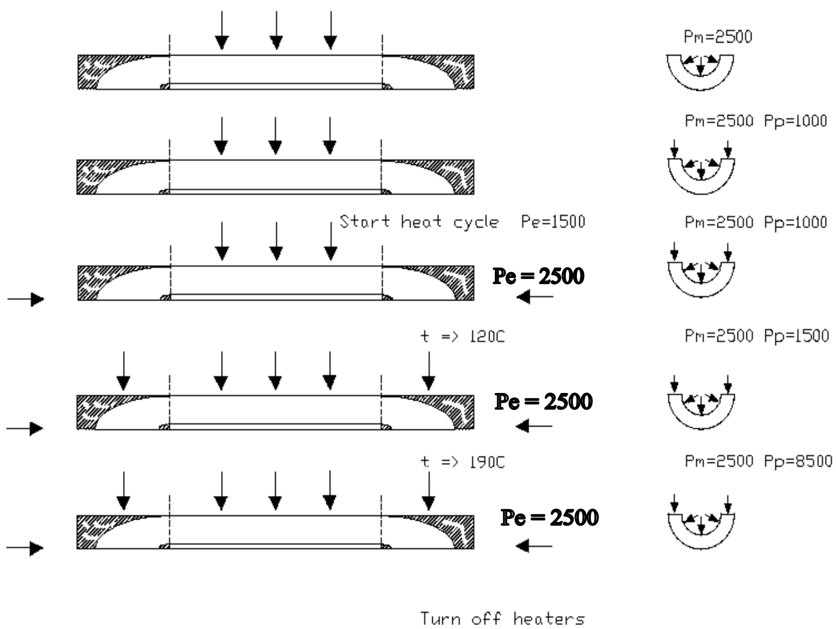


Fig. 1: *Curing Cycle for HGQ-03 coils. P_m = Mandrel pressure (Psi); P_p = Platen pressure (Psi); P_e = End pressure (Psi).*

Pressures listed in Fig. 1 are pump Psi of the cylinders. Relationships between these and coil Psi are described in TD-98-051.

4.3 Copper Stabilizer

A copper stabilizer (15 mm thick and 30 mm long piece of copper block with same width as that of the cable) was soldered on to the cable at the LE of the coils after curing to protect the cable from collapsing during the magnet assembly process.

4.4 Coil Body Size and Modulus

The coil azimuthal size and modulus measurements were taken over a range of pressures, 8000 Psi to 14000 Psi. The design pressure for both coils when cold and unpowered is 12000 Psi or 83 MPa. Coils were measured with 3 inch gauge length along the straight section of the magnet, from LE to RE. The ends of the magnet were measured separately using end-compression unit and will be discussed in the next section.

Tables 6 and 7 list the coil numbers and the corresponding average coil size and modulus. Comparing with HGQi-021 (the HGQ-03 R&D coil), the inner coil modulus decreased from 8 GPa to about 5 GPa; but there is significant increase in the coil size from 83 μm to about 260 μm (as expected) with the increase in cavity size by 20 mils. The outer coils size and modulus are fairly consistent with the R&D coil, HGQo-015.

Coil #	Coil average modulus [GPa] at pressure range 55-97 MPa		Coil size at 83 MPa coil pressure [μm]			
	Average	Stand. Div.	Side A	Stand. Div.	Side B	Stand. Div.
HGQi-023	5.09	0.25	284	20	298	20
HGQi-024	4.99	0.16	270	12	263	14
HGQi-025	4.94	0.23	254	8	267	16
HGQi-026	5.01	0.17	267	8	264	12

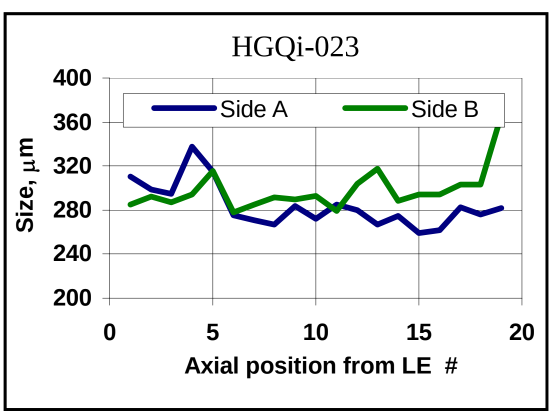
Table 6. *Inner Coil body size and Modulus.*

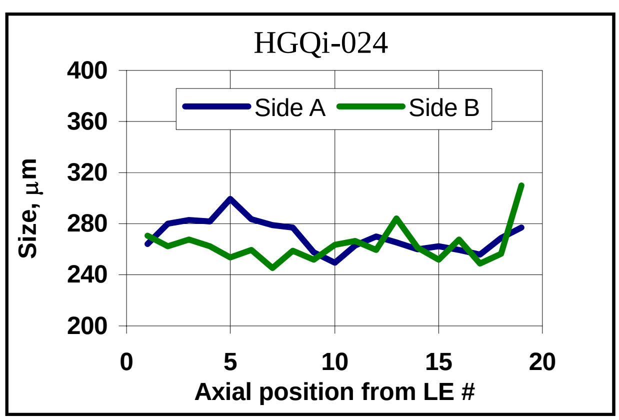
Coil #	Coil average modulus [GPa] at pressure range 55-97 MPa		Coil size at 83 MPa coil pressure [μm]			
	Average	Stand. Div.	Side A	Stand. Div.	Side B	Stand. Div.
HGQo-016	9.92	0.5	243	20	216	19
HGQo-018	10.12	0.56	239	22	222	18
HGQo-019	9.47	0.63	238	27	217	24
HGQo-020	10.1	0.71	248	26	226	25

Table 7. *Outer Coil body size and Modulus.*

The eight inner and outer coils shown in the tables above were used in the magnet HGQ-03. The one spare inner coil, HGQi-022 was destroyed during the end-compression testing and the spare outer coil, HGQo-017 is still available.

Variation of the coil size along the length of the coils are shown in Fig 2. Note that Side A is the winding side of the cable and the lead end of the cable is on Side B.





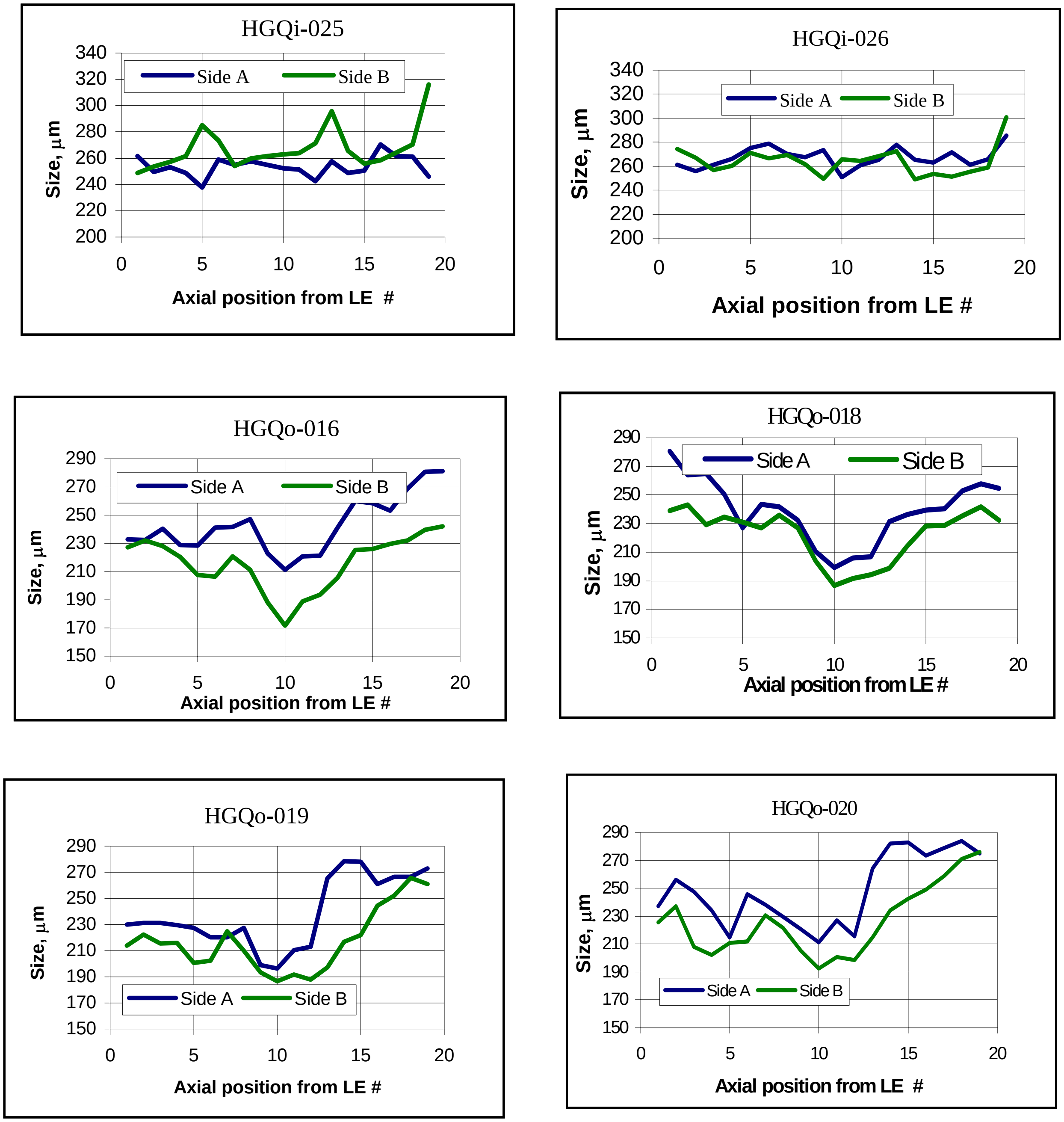


Fig. 2: *Variation of the coil size for both inner and outer coils along the length of the magnet.*

4.5 End-Load Experiments

End-compression experiments were performed to determine the end-shape and size of the coils. Unlike in HGQ-02 coils, a one inch pusher block was used to get a more precise shape of the coil ends. As these tests are very destructive, only R&D coils were tested and taking into account that the coils used in HGQ-03 are quite similar to that of the R&D coils, the data was considered sufficient.

Figs. 3 to 9 show the end-size data and modulus for LE and RE of both inner and outer coils. The large drop in size is near the large current block or position 3. The measurements are taken at both 6000 and 12000 coil Psi so as to obtain the modulus. Note that the modulus at position 3 is quite low compared to the straight section. Therefore the position 3 is not only undersized but also soft.

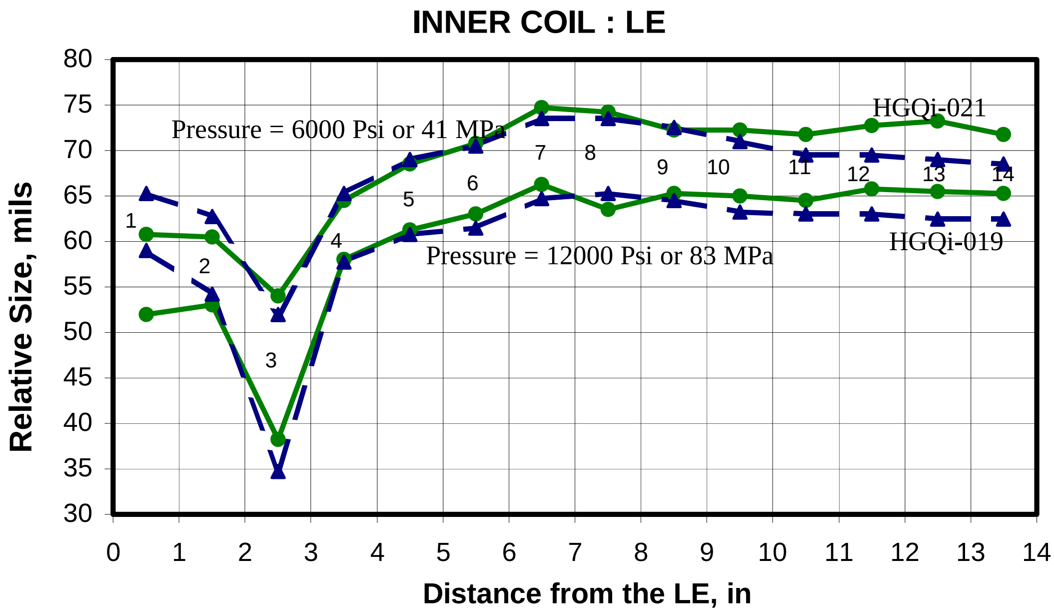


Fig. 3: *LE Shape for the inner coil. Note that the coil, HGQi-019 is with a left lay cable.*

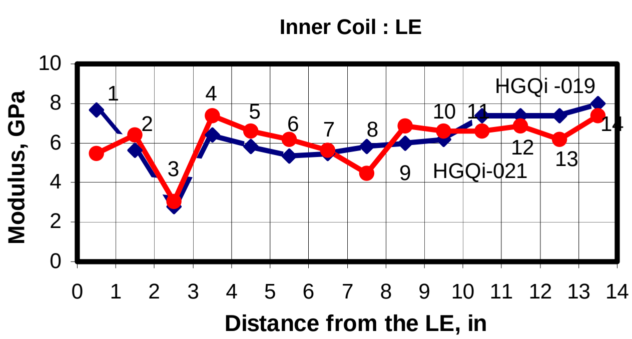


Fig. 4: *Variation of the coil modulus along the LE of the inner coils. Note that the modulus of the straight section for HGQi-019 and HGQi-021 = 8.0 GPa.*

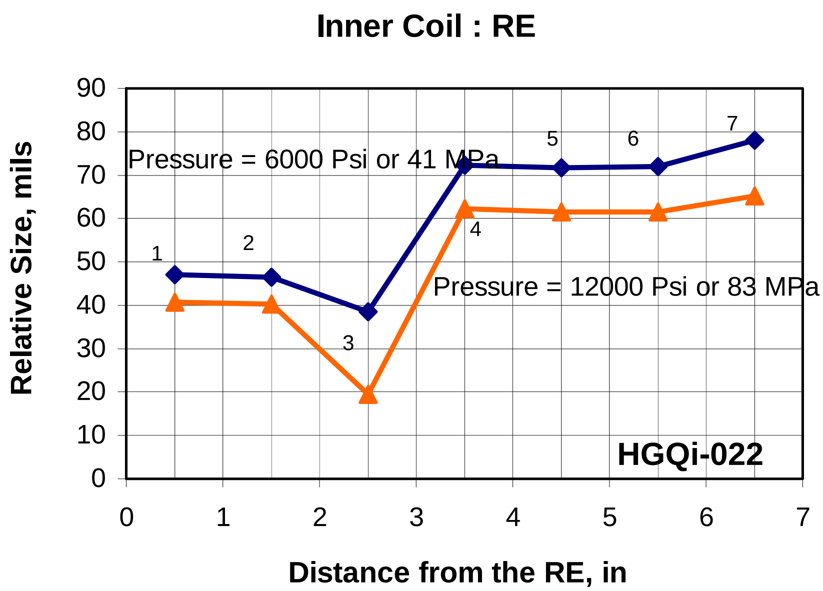


Fig. 5: *RE inner coil size variation.*

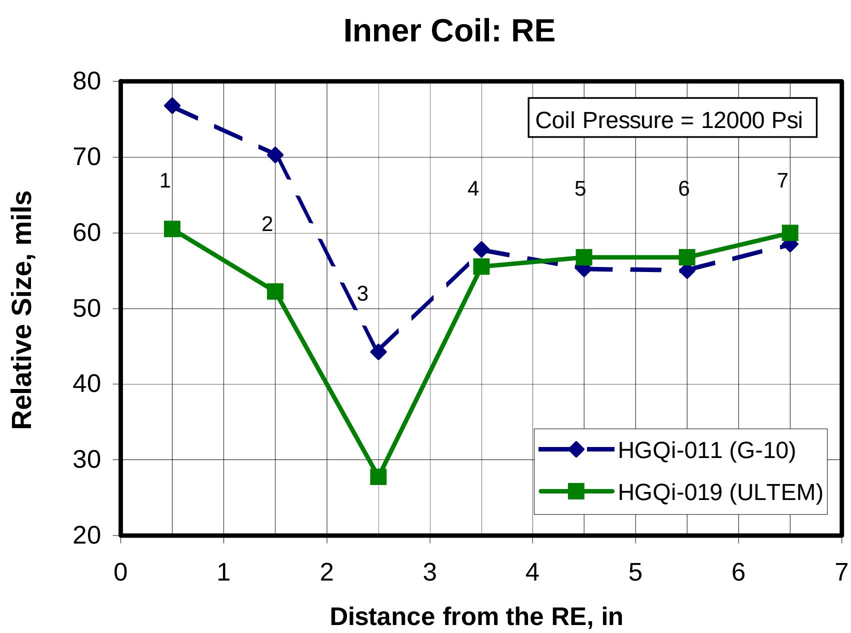


Fig. 6: *Comparison of the RE of the inner coils with G-10 and ULTEM end-parts.*

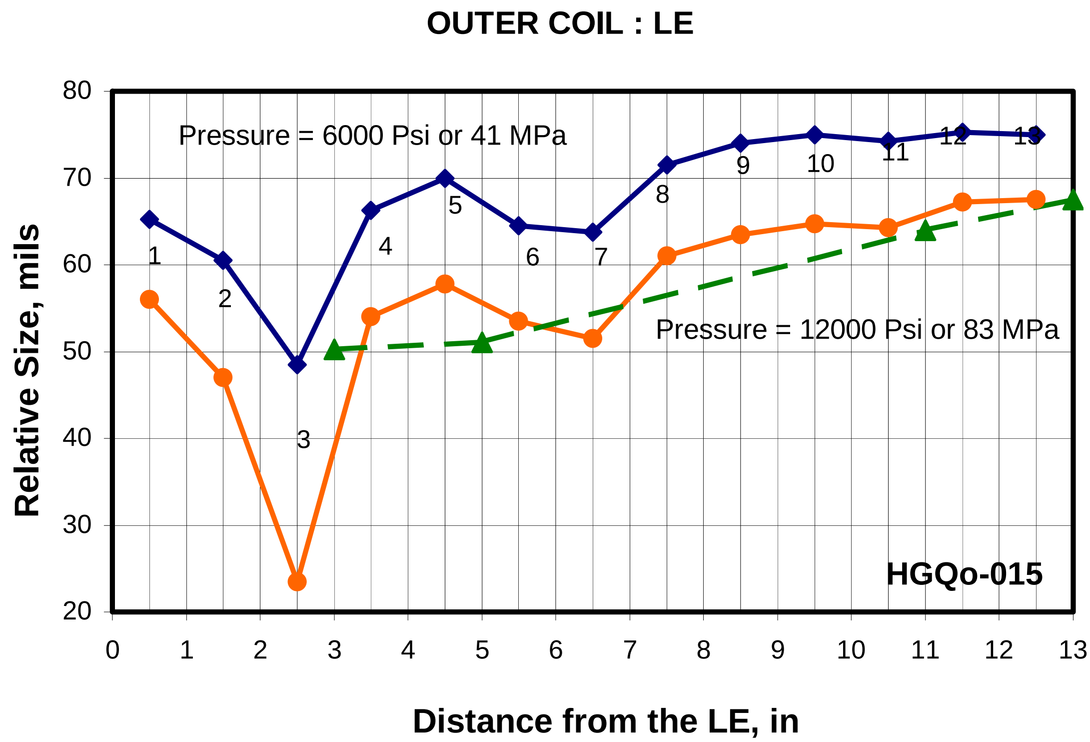


Fig. 7: *Variation of the coil size in the outer coil LE. The dotted line represents the measurements taken with 6 in gauge bar similar to that of in HGQ-02.*

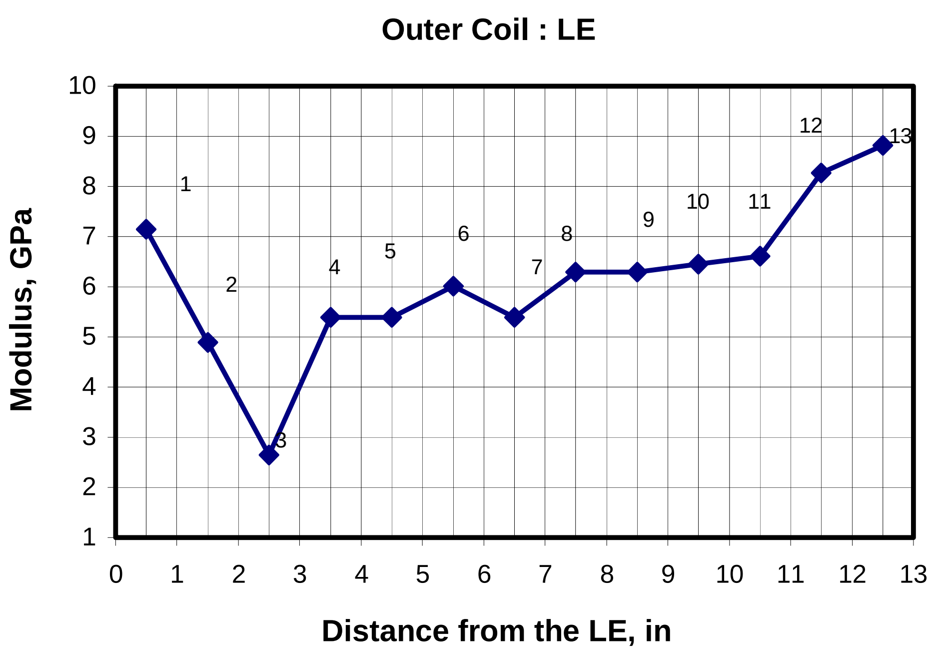


Fig. 8: *Variation of the modulus in the outer coil LE.*

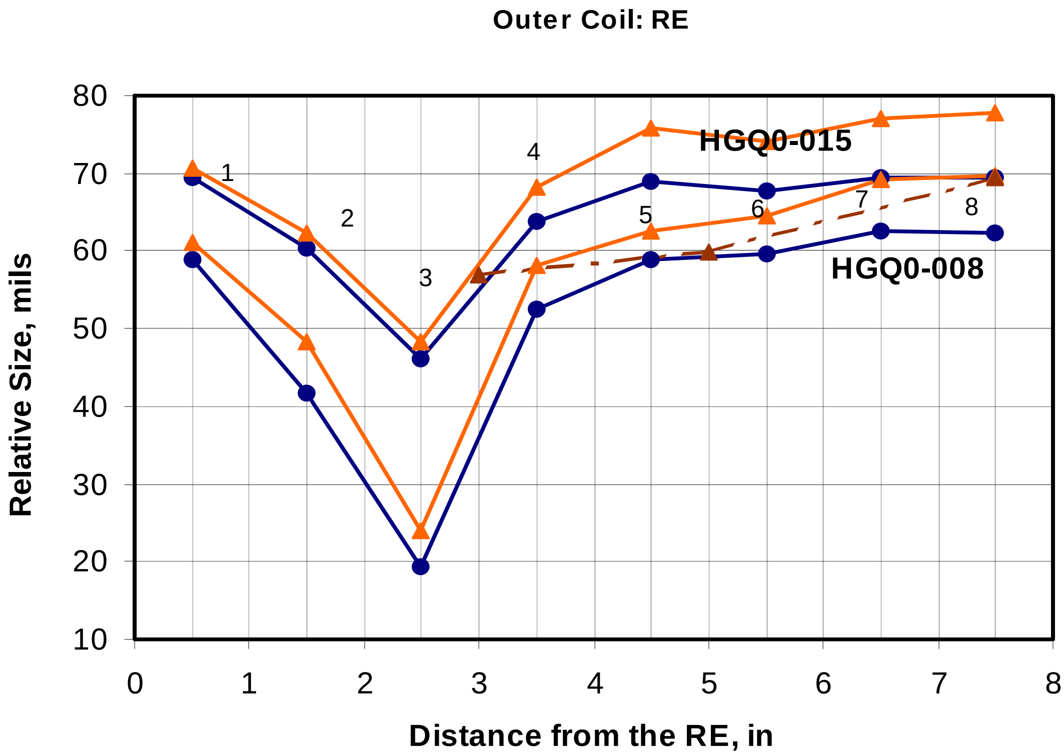


Fig. 9: *Variation of the coil size in the outer coil RE. The dotted line represents the measurements on HGQo-015 with 6 inch gauge block.*

4.6 Voltage Taps and Spot Heaters

Voltage taps were mounted according to the drawing number 5520-MD-344883 for inner coils and 5520-MD-344884 (Rev. A) for outer coils. The same technique used for installing the voltage taps in HGQ-02 was also employed for this magnet. The end-compression tests with 6 inch pusher bar were done on the HGQ-03 coils after putting the voltage taps to check for turn-to-turn shorts. None of the coils showed any shorts. However after two weeks we noticed that that the lead end saddle on an inner coil, HGQi-023 was cracked. The crack was initiated near the large current block where the edge of the pusher block sits during the compression testing. It was later replaced with a new saddle. Five minute epoxy was used to attach the saddle onto the coil and the end-compression fixture was used to apply the azimuthal pressure.

Two spot heaters one in the splice region and the other at the parting plane were mounted one two inner coils (HGQi-024 and HGQi-025). Two more spot heaters, one each at the parting plane were also mounted on outer coils, HGQo-019 and HGQo-020. The exact locations for these spot heaters are as per the drawing numbers 5520-MD-344883 and 5520-MD-344884 (Rev. A).

5.0 Coil Assembly

5.1 Preload Adjustments: Magnet Body

The targeted coil prestress for both inner and outer coils in HGQ-03 is 83 MPa (or 12000 Psi). This corresponds to a coil azimuthal size of +375 μm for inner coils and +250 μm for outer coils at 83 MPa. The inner coils body size vary between +254 and +298 μm; so they had to be shimmed up by 100 μm or 0.004 in. Similarly the outer coils body size vary between 216 and 248 μm; so they had to be shimmed up by 25 μm or 0.001 in. However it was latter decided not to shim the outer coil body as the preload levels in the HGQ-02 outer coils were very high. All coils were shimmed at the parting plane from the end of saddle on the LE to end of saddle on the RE. The coil placement and the shim sizes are shown in Fig. 10.

HGQ-03 Coil Placement and Shim Size. Data: 05-20-98 R.Bossert/D.Chichili

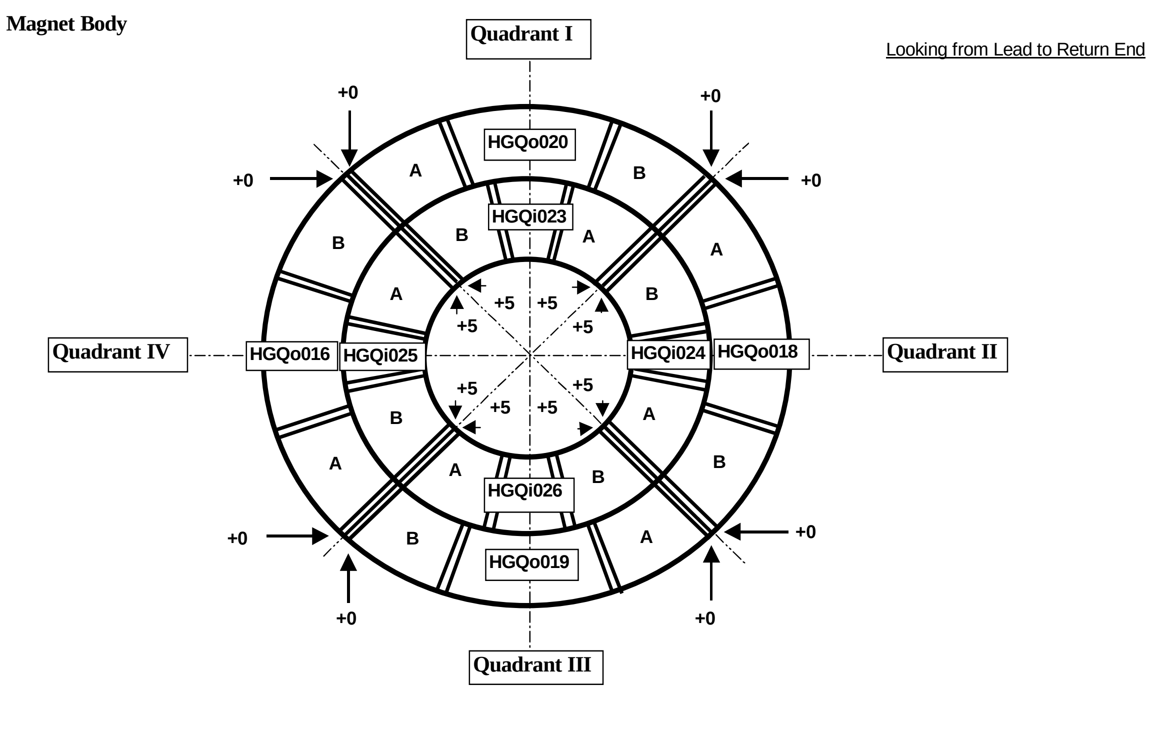


Fig. 10: *The coil placement and shimming for the Magnet body.*

NOTE: The inner coils are shimmed 5 mils instead of 4 mils so as to account for kapton deformation at 83 MPa which is measured to be approximately 30%.

5.2 Preload Adjustments: Magnet Ends

The shape of the magnet ends is much more complicated than that of the magnet straight sections as shown in section 4.5. The following is the summary of the meetings held during the third and fourth week of June 98 for deciding the end-shimming for HGQ-03.

For HGQ-02, the end size for both LE and RE of Inner and Outer coils were measured with a 6 inch gauge pusher bar. Based on the test results from HGQ-02, it was decided that the end size should be measured instead with a one inch pusher bar. The test results from three R&D inner coils (HGQi-109, HGQi-021 and HGQi-022) and two R&D outer coils (HGQo-008 and HGQo-015) with a one inch pusher bar were latter analyzed. The results showed that there is a gradual, uniform decrease in the size from the body of the magnet to the end-saddle with the exception there is a big drop at the large current block (third measurement from the end of the saddle). For inner coil LE, the drop is about 27 mils, inner RE it is 45 mils, outer LE it is 43 mils and outer RE it is 45 mils. Note that these drops are with respect to the body size. The tests were done at both 6000 and 12000 coil Psi to estimate the modulus of the end. The modulus at the third position is around 2.5 GPa compared to 10 GPa for the outer coil straight section and 8 GPa for the inner coil straight section. This shows that the third position is much softer than the rest of the magnet.

Based on the discussions, a preliminary shimming plan was formulated. It was agreed upon that the amount of shimming should be added to take into account for cool down losses, kapton deformation and to rise the end part deformities only to have a smooth drop in pre-stress (instead of rising the end size to that of the body size). This was considered to be a conservative move for two reasons (i) preload in the ends does not necessarily have to match with that of the straight section as the magnetic fields in the straight section are higher than that in the end and (ii) the amount of kapton to rise the size of the end to that of the body is too high if you take into account the kapton deformation. Also as most of it is concentrated in a small area (1 inch length) it might cause stress concentrations in the end-saddle during collaring and keying.

The following is the end-shim plan which came out of these discussions (this was subsequently changed to the final shim plan shown in Appendix-III; Figs. 11 to 14. Explanation of the changes is on Pgs 18-19.

INNER COIL: LE

(a) 5 mils of body shimming
(b) 3 mils for cool down loses at the key and 5 mils at the spacer.
(c) 3 mils to account for kapton deformation for above two
(d) 22 mils (17 + 5 mils for kapton deformation) at the third position to account for end-part deformities. 5 mil increments with a step of an 1/8th of an inch was chosen.

INNER COIL : RE

(a) 5 mils of body shimming
(b) 5 mils for cool down loses
(c) 3 mils to account for kapton deformation
(e) 33 mils (26 + 7 mils for kapton deformation) at the third position to account for end-part deformities. 5 mil increments with a step of an 1/8th of an inch was chosen.

OUTER COIL: LE

The original plan (derived after testing with 6 inch gauge length) was to shim a total of 30 mils (21 mils for end-part deformities + 2 mils for cool down loses + 7 mils for kapton deformation). The kapton shims were feathered with a 1 inch step. Note that the LE was not divided into Area-1 and Area-2 as done in HGQ-02.

After testing with a one inch pusher block, a total of 34 mils (26 + 8) had to be added at the third position from the end of the saddle. Instead of changing the entire earlier shimming scheme, it was decided that an additional 3 mil thick kapton will be added at the third position, bringing it to 33 mils. Note the feathering system will automatically takes into account the new cool down looses and the corresponding kapton deformation.

OUTER COIL: RE

As with LE, the original plan (derived after testing with 6 inch gauge length) was to shim a total of 26 mils (18 mils for end-part deformities + 2 mils for cool down loses + 6 mils for kapton deformation). The kapton shims were feathered with a 0.5 inch step.

The end-part deformities in RE as measured by the one inch pusher block was found to be much severe than that in LE (this is something which was observed consistently in both inner and outer coils). The shimming required to take into account the drop in size at the third position was about 40 mils (30 +10). Keeping the earlier shimming scheme, it was decided that 13 mil shimming (3+5+5) will be added at the third position bringing it to 40 mils. As with the LE, the cool down loses are already taken into account.

The R&D coils tested previously were shimmed accordingly and retested with one inch pusher block. The objective of these tests was to test the shimming plan, to measure the horizontal motion of the end-saddle during these tests and to check turn to turn shorts during compression. Also a radial shimming was introduced at the large current block to reduce the motion of the cables. The test results were consistent with slightly more drop at the large current block than expected. This might be due to the fact that some of the saddles were broken during the earlier tests. The measured axial motion for an outer coil RE with a broken end-saddle was about 70 mils. When an inner coil with good end-saddle was tested, the axial motion was about 14 mils at 6000 coil Psi and 19 mils at

12000 coil Psi (note that when measured with 5 inch gauge length the motion was about 1.5 mils at 12000 Psi). There were no turn to turn shorts during compression.

As a final confirmation, an R&D inner coil and an R&D outer coil made for HGQ-04 were tested with the proposed shim plan. Note that the length of the end-saddles were reduced for HGQ-04 by about 20 mm. Surprisingly the end-saddles broke during the first squeeze. However the failure mode was completely different from that of the previous coils. In the earlier coils, the saddle broke underneath the pusher block. However for R&D coils made for HGQ-04, the crack initiated at the free surface of the saddle and propagated towards the coil. In fact for HGQi-027, the saddle broke into two pieces and flew off while testing. In light of these results, it was latter decided that we will remove 13 mils from the inner coil RE, 8 mils from inner coil LE, 3 mils from outer coil LE and 11 mils from outer coil RE, all at the third position from the saddle. It should be noted here that the loading conditions in the end-size testing procedure are not the same as in collaring-keying. During these tests we are pushing with a one inch block with ends not supported. However during collaring and keying a four inch section is squeezed with a three inch key being pushed in place. So the testing procedure merely shows what not to do. To further confirm this reduction in shimming size, an SSC outer coil RE was tested with one inch pusher bar to see if there is any drop in size. The magnets made out of similar coils were supposed to have reached the short sample limit without much training. The end-compression results (Fig. SSC) showed that even SSC coils had similar drop in size at the large current block. So in retrospect reducing the amount of shimming at the ends seems to be a good idea.

The final shimming plan which was implemented in HGQ-03 is shown in the Appendix-III (Fig. 11 to 14). The kapton thickness values in all the figures are in mils. Note that the shimming in the outer coil was feathered with respect to the adjacent outer coil so that the steps does not coincide at the same locations.

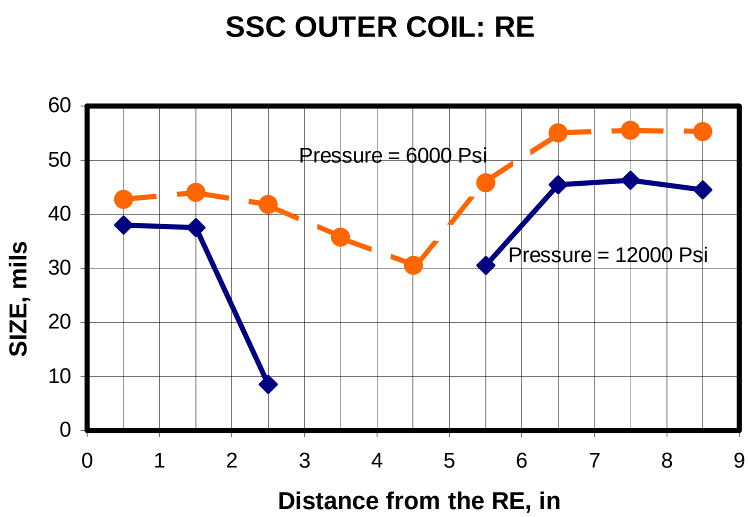


Fig. SSC: *Variaiton of coil size for an SSC outer RE.*

5.3 Ground Insulation and Strip Heaters

The ground insulation scheme is pretty much the same as in HGQ-02. Quench protection strip heaters were placed between the inner and outer coils and between outer coils and the collars. Standard strip heaters were placed between the inner and outer coils, where as optimized strip heaters with copper coating from LBNL were placed between the outer coils and the collars. To mount the outer coil strip heaters, a layer of kapton sheet (125 μm thick) was removed. The standard heaters consists of a 25 μm stainless steel strip covered on each side by a 25 μm kapton "cover sheets" which gives a total of 75 μm thick strip heater assembly. LBNL strip heaters consist of stainless steel strip coated with copper and covered on each side by kapton "cover sheets". The total assembly is 150 μm (6 mils) thick. As with HGQ-02, there was atleast 125 μm Kapton insulation between the heaters and the collars at the transition and in the end regions. The ground wrap insulation at the LE and RE was carefully mounted to ensure that there is no potential for heater to collar ground short.

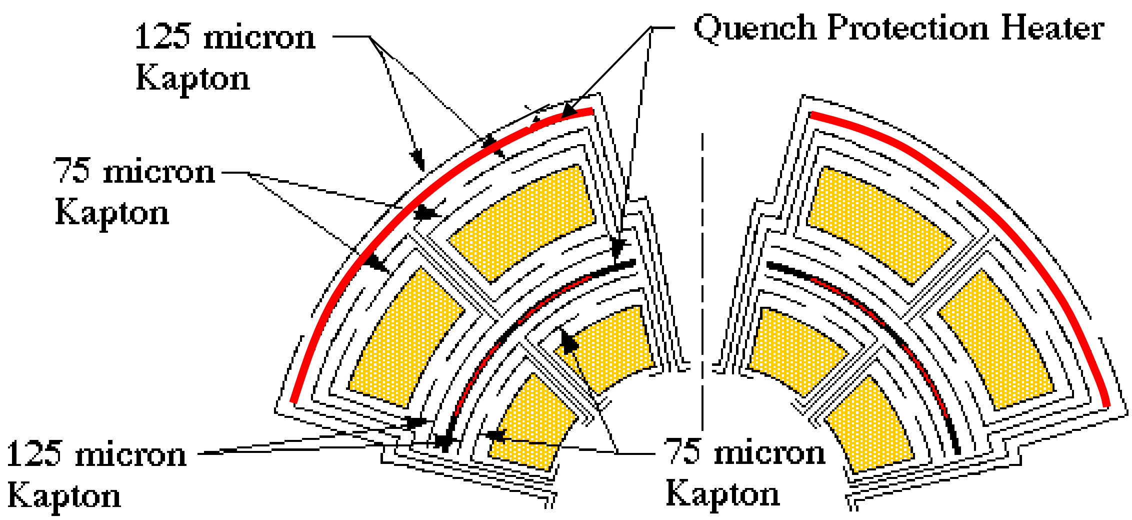


Fig. 15: *Ground insulation scheme and the strip heater locations.*

5.4 Pole Extensions

Ultem pole extensions which are 9.8 mm (3/8 in) long are placed at the back of the Ultem keys on both lead and return ends. These extensions fill the pole space of both inner and outer layers near the transition otherwise filled by the collar laminations. On the lead end of the magnet unmodified pole inserts were mounted whereas on the return end, pole inserts were modified to fill the spaces between the collars and the Ultem keys because of different coil lengths. A good drawing depicting this is given in the HGQ-02 production report.

6.0 Collaring and Keying

6.1 Collaring: Magnet Body

HGQ-03 being an internal splice magnet, the entire length is collared and keyed. The standard collar laminations are stacked in the straight section and full round collar laminations are stacked in LE and RE. The locations for strain gauge collar laminations were determined based on the coil size data. The locations at which the coil size is lowest and highest is chosen so as to obtain the variation in the coil prestress. Figs. 16 and 17 show the mid-plane coil size data along the length of the magnet for all the four quadrants.

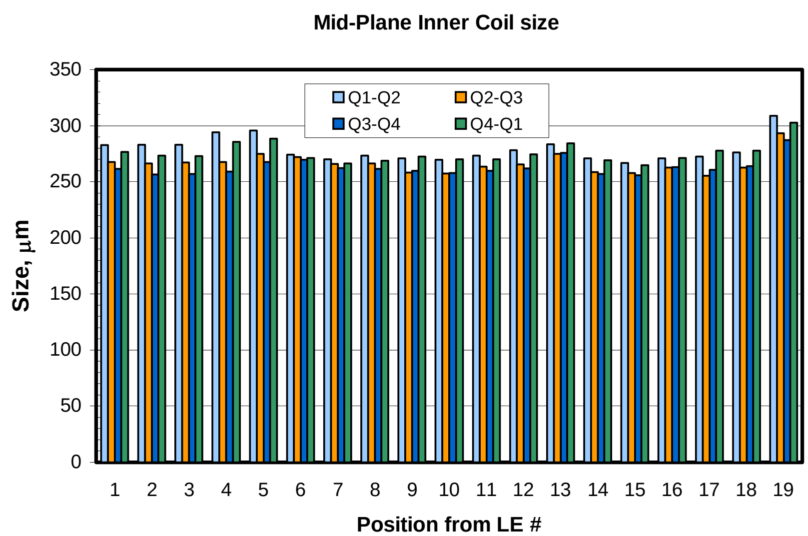


Fig. 16: *Inner coil size by quadrant along the length magnet.*

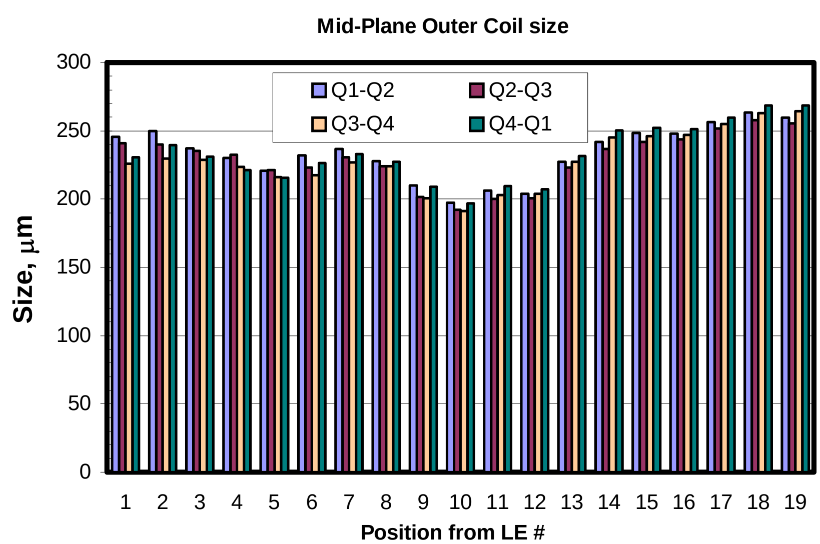


Fig. 17: *Outer coil size by quadrant along the length of the magnet.*

The inner coil size stays pretty uniform through out the length of the magnet in all the four quadrants. However outer coils show gradual drop in size from LE to the middle of the magnet. Hence position #10 and 18 are chosen for strain gauge locations as position #10 has the lowest coil size and position #18 has the largest coil size (see Fig. 17).

Two inner beam gauges, two outer beam gauges and two capacitor gauges are placed at each location. Further each location also has two temperature-compensating gauges. The gauge placements at each location are shown below:

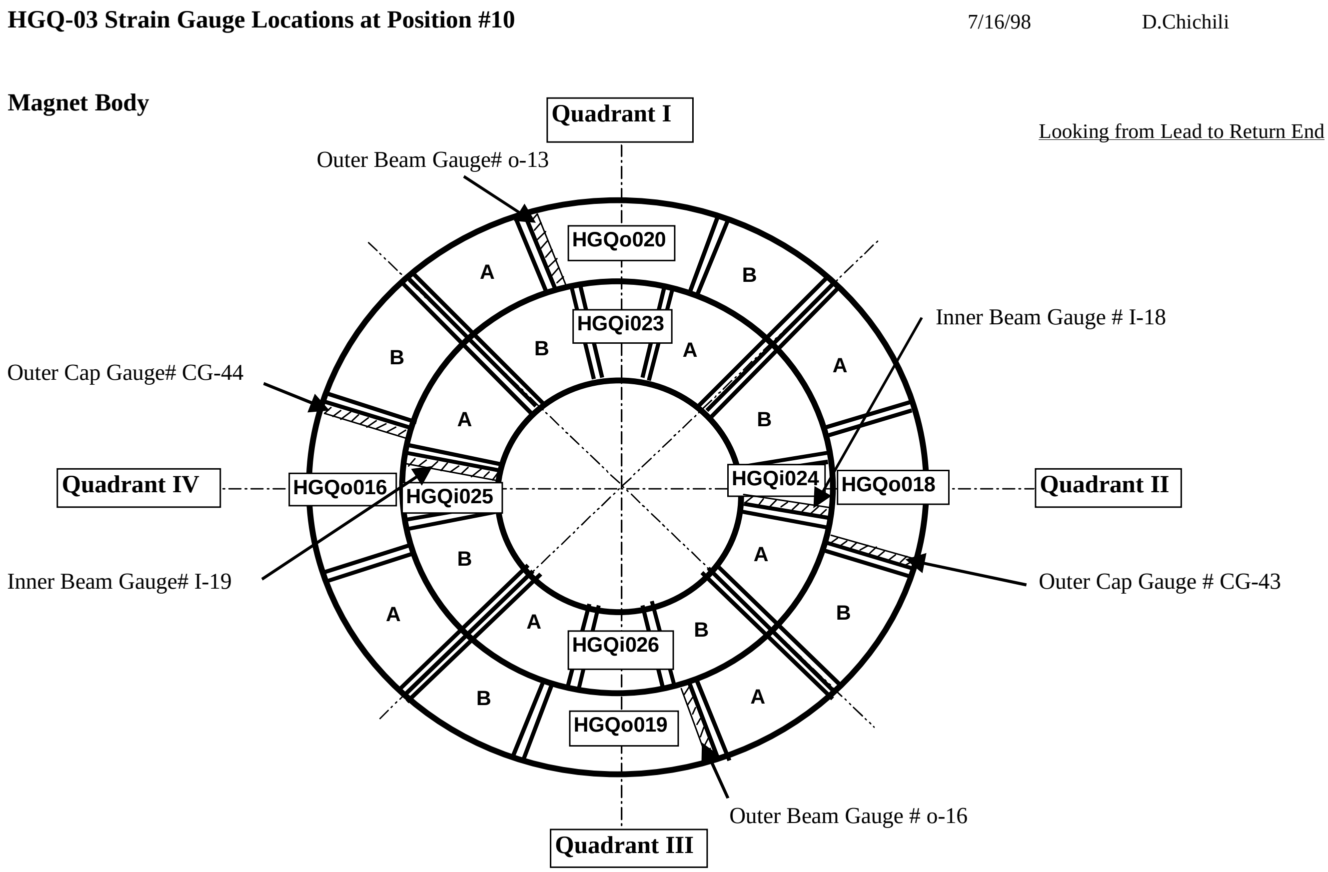


Fig. 18: *Magnet cross-section at Position #10 showing the Strain Gauge Locations.*

HGQ-03 Strain Gauge Locations at Position #18 7/17/98 D.Chichili

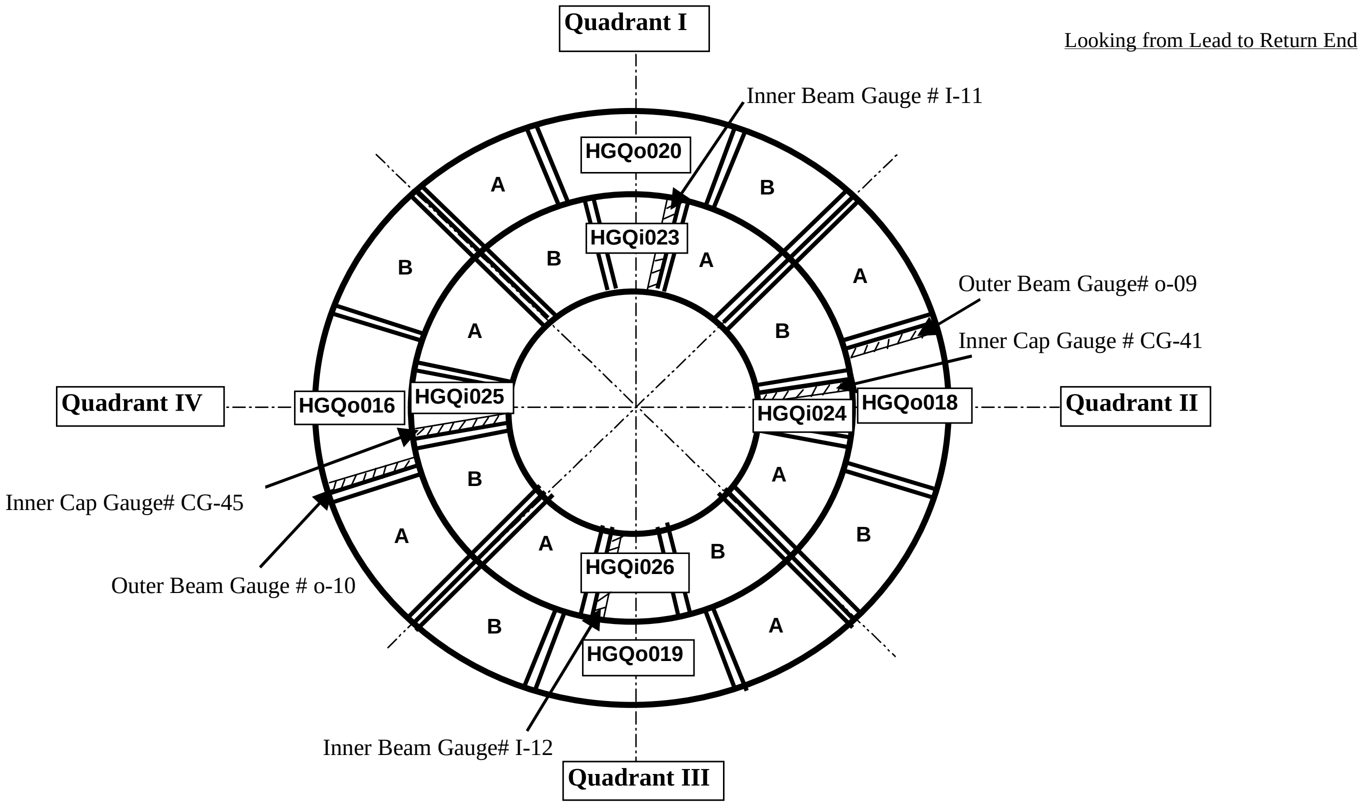


Fig. 19: *Magnet cross-section at position# 18 showing the strain gauge locations*.

6.2 Keying: Magnet Body

The vertical keying procedure similar to that used for HGQ-01 and HGQ-02 was used to key the magnet. The straight section was collared and keyed before repeating the same for LE and RE. Once the straight section was stacked with standard collar laminations, the magnet body was massaged at 1500 and 3000 pump Psi. The collar outside dimensions were measured during massaging at various points along the length of the magnet.

The keying procedure is designed to minimize the over compression of the coils as much as possible. It was shown that repeated loading and unloading at lower pressures ("toggling") decreases the peak stress in the coils (decreases springback) and hence decreases the risk of turn to turn shorts. The collared-coils are first compressed using the main hydraulic press at pressures ranging from 6500 to 7500 pump Psi. This allows to partially insert the keys manually. Then the keying pressure of 3000 pump Psi was applied. After which the main press was released and pressurized again. This process was repeated 3 times. During this process the keying pressure was on and this loading and unloading of the main press drives the key into the groove. Finally all the pressures are released and the collars are held by keys alone. Figs. 20 and 21 show the distance between the pushers along the length of the magnet at various pressures.

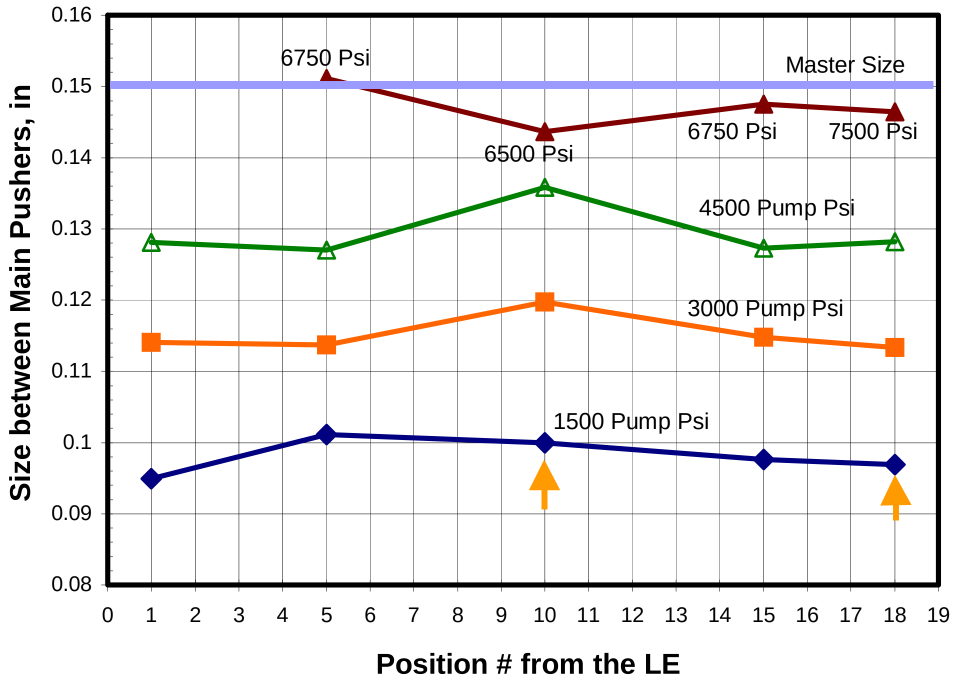


Fig. 20: *Massaging history of HGQ-03 during keying procedure*

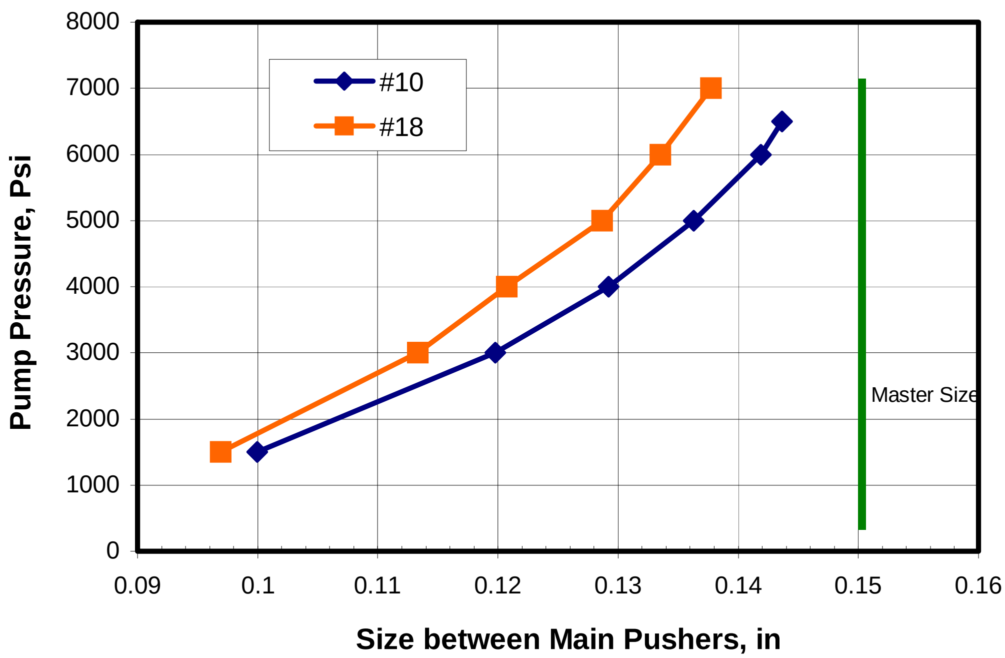


Fig. 21: *Massaging history at the Gauge Locations.*

The variation of the coil pressure during the massaging is shown in the Fig. 22. Inner coils always seem to start of at higher pressures than that of outer coils (similar behavior was observed in HGQ-02); however outer coils usually catch up with inner coils at higher pressures. This is partly because outer coils have higher Young's modulus than that of inner coils. Fig. 22 shows that the outer coils never catch up with the inner coils and it is still not clear why this happened. The major distinction between HGQ-02 and HGQ-03 coils is the magnitude of the coil pressure for the given pump pressure. HGQ-03 inner coils showed very high stress levels compared to HGQ-02 inspite of the fact that distance between the pushers is about the same. The two inner and two outer gauge readings at a location are averaged in the plot shown below.

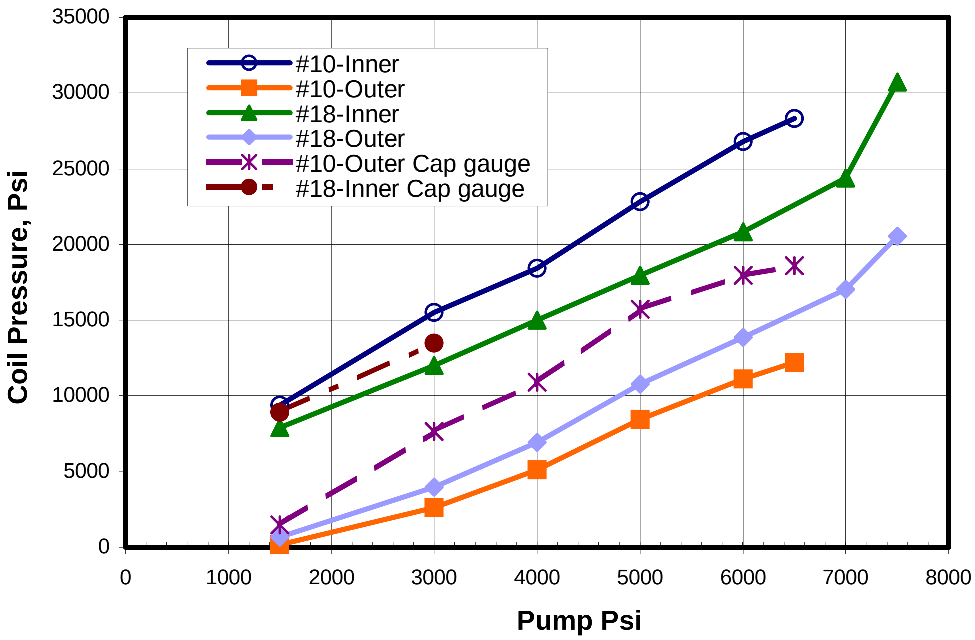


Fig. 22: *Variation of the coil pressure with respect to the pump Psi. Note that the inner cap gauges failed at 3000 pump Psi.*

The final pre-stress values in the magnet are given in Table 8. Note that all the gauges are in the body of the magnet. The beam gauges and cap gauges are placed at opposite poles, so in theory they should read the same preload. Further the beam gauges and the cap gauges are placed in the same quadrant should also read similar preloads. NOTE: the coils were keyed first at position #10 (the middle of the magnet) and then keyed upwards to position #1. Later the keying started at position 11 and went downwards to position # 19. The inner coil pre-stress values are very high compared to that of the previous two magnets. One of the inner beam gauges (I-12) read as high as 43 Ksi before the spring-back and we know that the steel in the strain gauge beams yield at around 33000 coil Psi (this corresponds to an internal stress in the steel beams of 105000 Psi). Hence we need to be cautious in using these strain gauge readings at their face value.

Gauge position and number	Coil stress before "springback". (Main pump pressure 6500 - 7500 psi, key pressure 3000 psi.) 07/25/98		Coil pre-stress after "springback". Keys alone support coils. 07/25/98		Coil pre-stress after yoking and skinning. 08/07/98	
Position #10	Psi	MPa	Psi	MPa	Psi	MPa
Inner beam gauge, I-18	35207	242	30306	209	30153	208
Inner beam gauge, I-19	28786	198	22353	154	22228	153
Outer beam gauge, o-13	15619	108	11083	76	10919	75
Outer beam gauge, o-16	13661	94	9314	64	9670	67
Outer cap gauge, CG-43	20062	138	12792	88	12070	83
Outer cap gauge, CG-44	21259	147	14038	97	12416	86
Position #18						
Inner beam gauge, I-11	27443	189	23316	161	22276	154
Inner beam gauge, I-12	42946	296	35999	248	33874	233
Outer beam gauge, o-09	27688	191	20799	143	20317	140
Outer beam gauge, o-10	23492	162	16069	111	15199	105
Inner cap gauge, CG-41	15334	106	failed		6901	48
Inner cap gauge, CG-45	failed		failed		14242	98

Table 8: *Coil pre-stress values at various stages of magnet fabrication.*

6.3 Collaring and Keying: Magnet Ends

Before collaring and keying the magnet ends, the pole turn of each inner and outer coil pair needs to be spliced together. Areas to be spliced are preformed (filled with solder before the coil is wound) and then joined using the splice fixture. A cooling fixture was attached at the coil side so that the coil is not heated up. The maximum temperature for the turn next to the heater during the splicing processes was about 140 F. The length of the internal splice is about 114 mm, approximately equal to the cable transposition pitch.

After the splice joints are performed, full round collars are stacked at both LE and RE. Similar to that of the magnet body, the ends are massaged first at 1500 and 3000 pump psi before beginning to key. The keying pressure varied from 6750 to 8500 psi. The highest pressure was at positions 5 to 9 in Figs. 3 and 7. This might be to due to the fact the these positions are highly shimmed. The transition area was first keyed to avoid any rotation of the round collars.

6.4 Collared-Coil Deflection Measurements

The outer diameter of the collared-coil assembly was measured with the mandrel and with out the mandrel. The measurements are made both at the mid-plane region and pole region. Since the gauge readings show very high pre-stress in the coils, the OD measurements will confirm or refute the strain gauge readings.

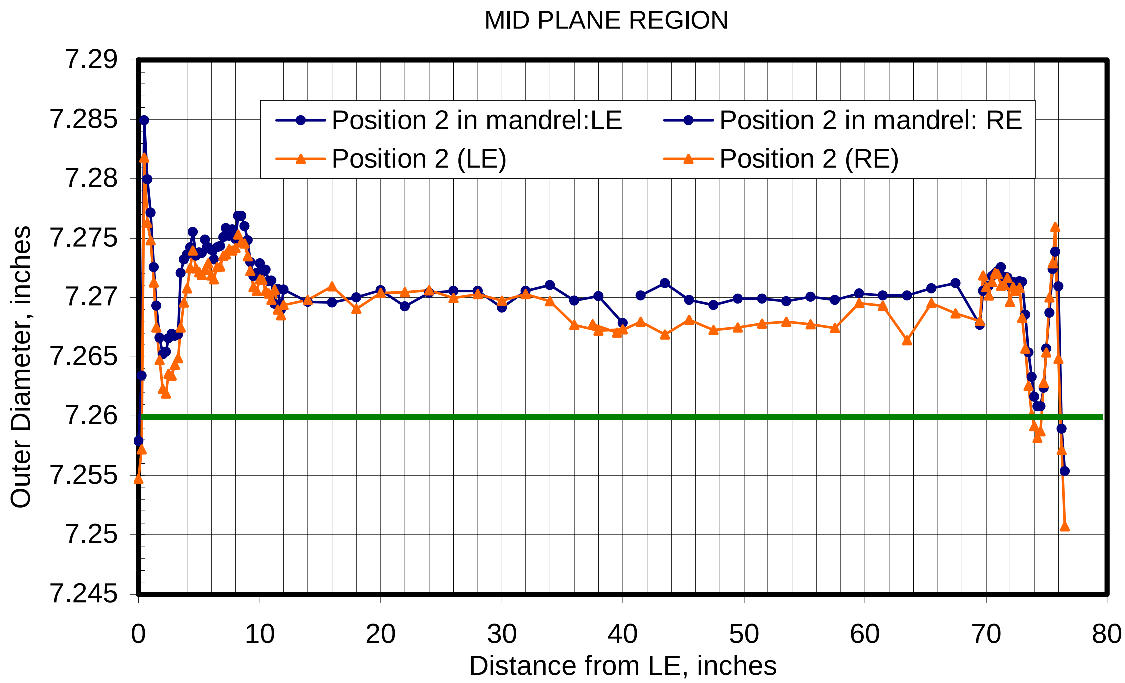


Fig. 22: *Deflection measurements at the mid-plane with and without the mandrel.*

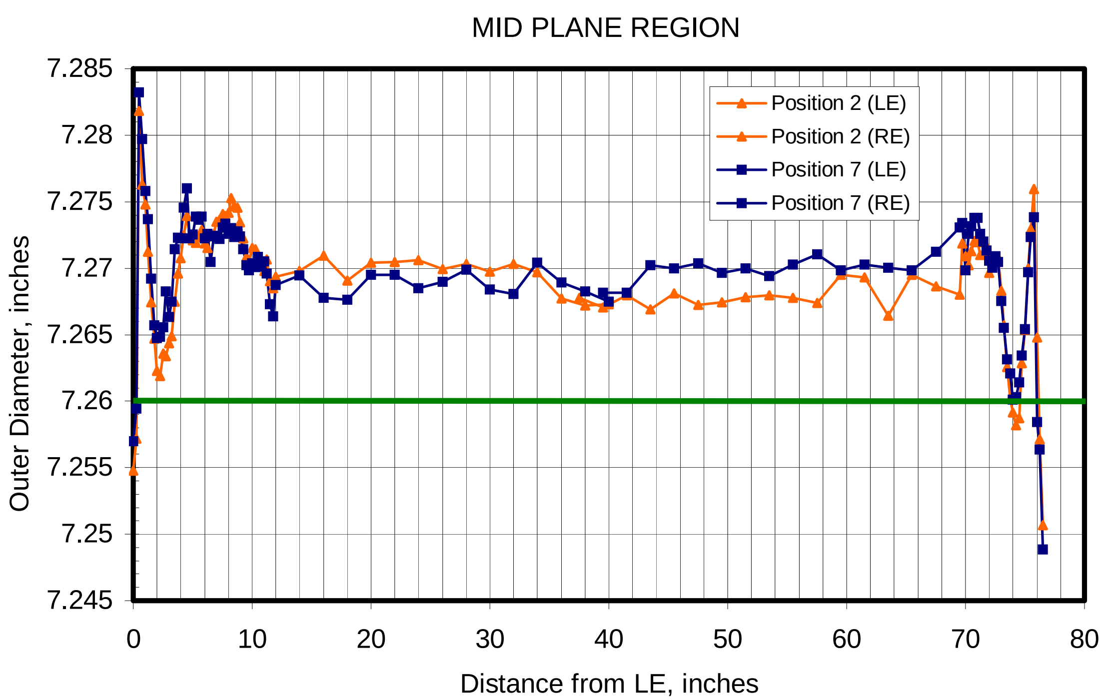


Fig. 23: *Deflection measurements at the mid-plane at two different positions (mandrel out).*

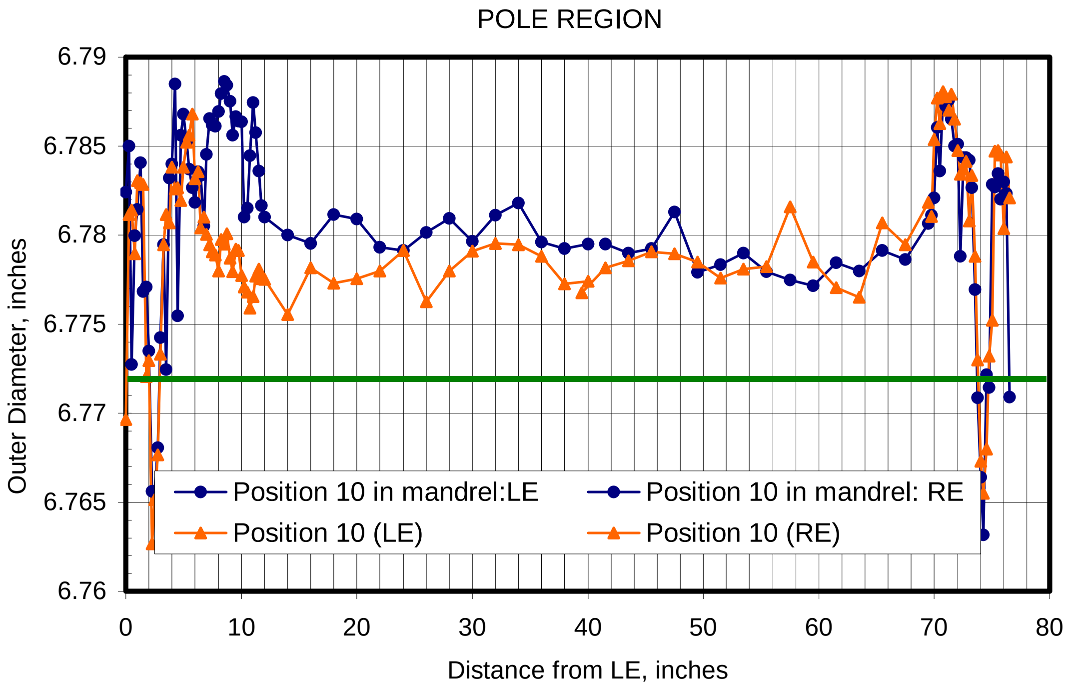


Fig. 24: *Deflection measurements at the pole region with and without the mandrel.*

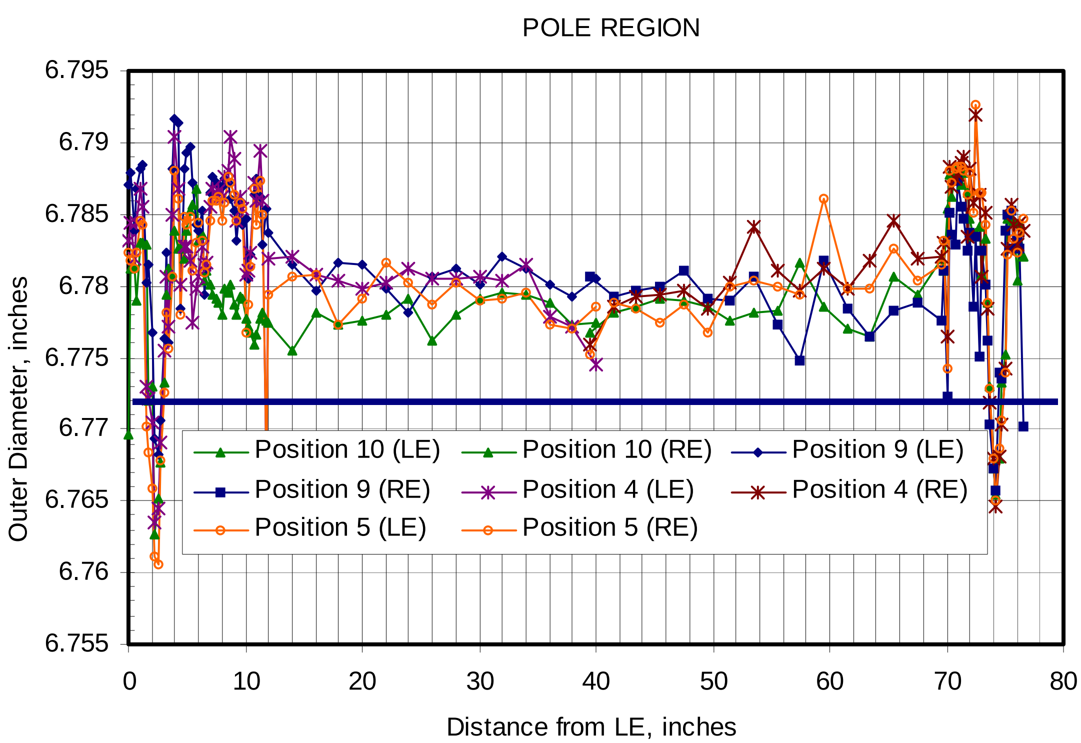


Fig. 25: *Deflection measurements at the pole region at various locations (mandrel out).*

Eventhough the strain-gauge readings show very high coil pre-stress data, the collared-coil deflection measurements in the magnet body are quite normal and the magnitude of the deflection is similar to that of in HGQ-02. FEA computations (TD-97-051, TD-97-004 and TD-97-009; via JimK) suggests that for standard collar laminations, there is 1.55 μm/MPa deflection on the radius and for full round laminations there is 2.1 μm/MPa deflection on the radius. Using these values we can estimate the coil pre-stress using the collared coil deflections measurements. Fig. 26 shows these estimates and the average coil-prestress is around 100 MPa whereas beam gauge measurements vary between 233 to 150 MPa for inner coils and 140 to 67 MPa for outer coils. However outer cap gauge measurements show 85 MPa but unfortunately inner cap gauges failed. Note that the reference OD by design is 7.26 inches but QC reports show that the collar laminations are off by 2 mils on radius and hence the OD for pre-stress estimates was considered to be 7.256 inches. This also implies that the entire length of the magnet has some pre-load under warm conditions (neglecting the last two data points which actually show the prestress in the end-saddle).

Inspite of the shimming at the magnet ends, the collared-coil deflection measurements show significant drop in the stress levels at both LE and RE. Comparing to HGQ-02, the magnitude of the drop at the RE is less by 3 mils. This is nowhere close to the amount of the shimming being added to the magnet ends. This question still needs to be addressed.

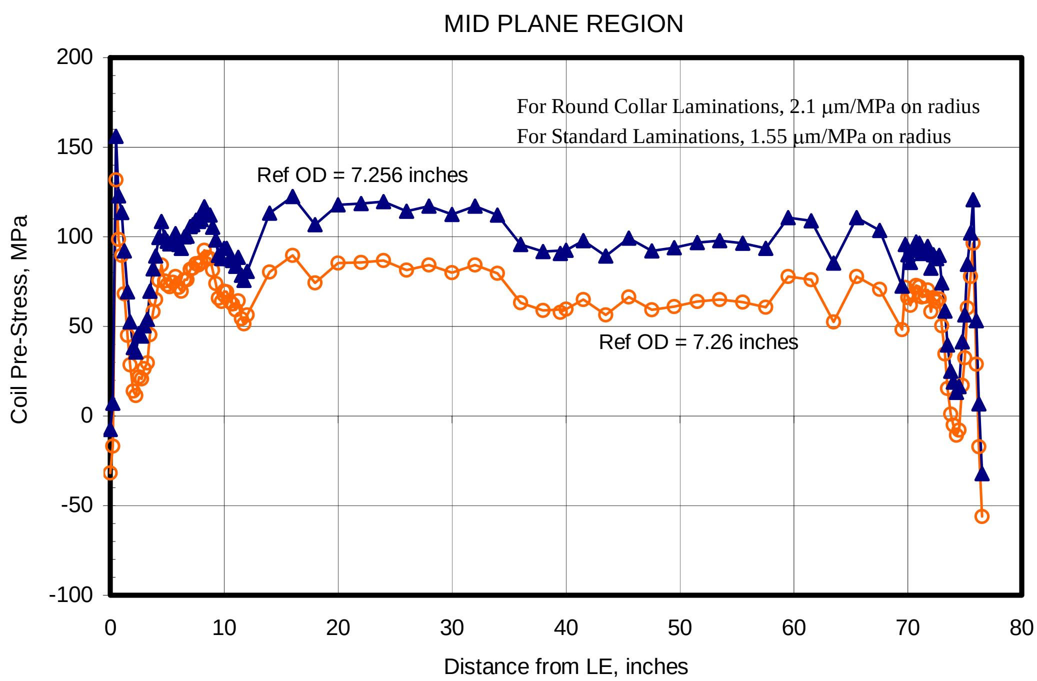


Fig. 26: *Coil-prestress estimates from collared-coil deflection measurements and FEA*

7.0 Cold Mass Assembly

It was decided that for HGQ-03 there will be no end-loading and hence the magnet cannot be supported by bullets. Note that there is no collet in this magnet as it has a internal splice design. This left us to design an anchoring system which will hold the collared-coil assembly within the yoke pack. A simple idea was to insert two tabs (1.4 inch long and 0.6 inch wide with the same thickness as collar laminations; in fact these tabs were machined out of standard laminations) between the laminations, 180^0 apart and glue them in place. These tabs rest on the yoke pack and can support the entire weight of the collared-coil assembly. The location of these tabs is at the transition between the standard laminations and the round collar laminations approximately the same location where the collet in the external splice design starts.

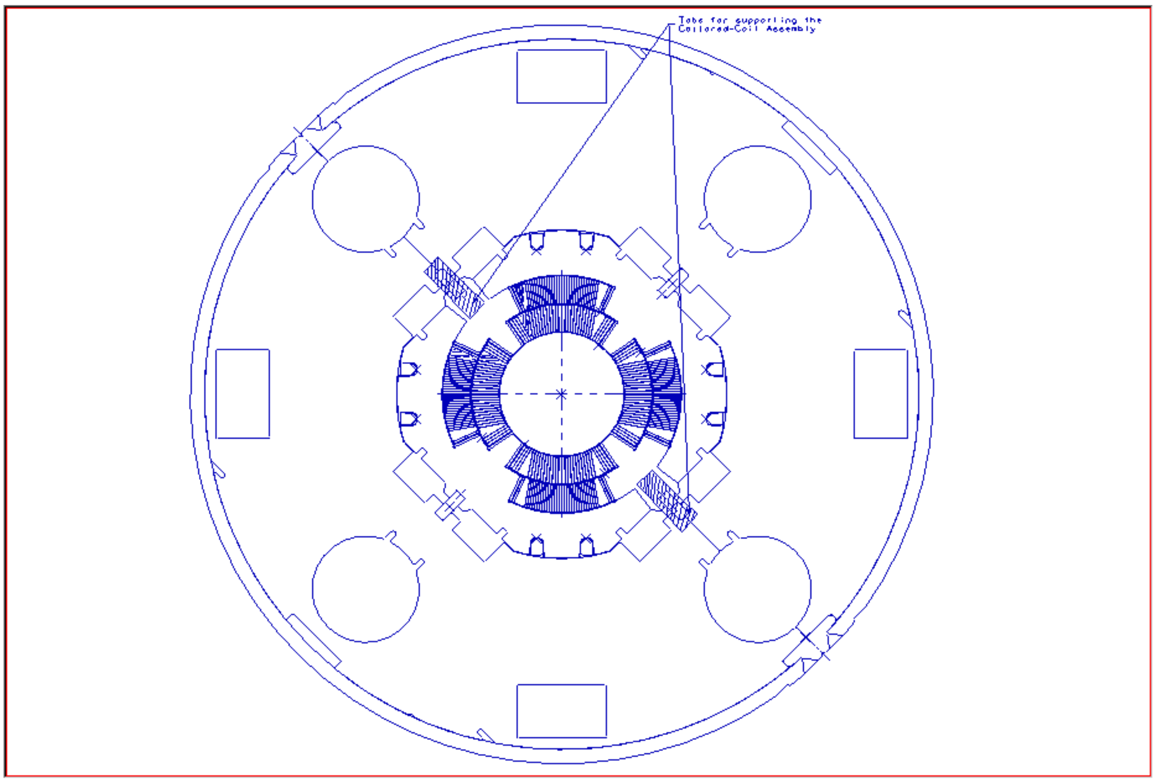


Fig. 27: *Collared-coil support system within the yoke pack.*

7.1 Yoking and Skinning

Due to the twist in the magnet lead and return ends it was decided to put collet yoke packs in the LE instead of stainless steel yoke pack and no yoke in RE. This way the magnet is truly not loaded in the ends. The twist as measured in IB3 was pretty much local in the ends, but during insertion in the yoke, a twist was apparent in the body as well. However, the total residual twist at the ends after the collared coil was placed in the lower yoke half was not done. The tabs were inserted between the iron yoke and the LE collet yoke pack. The following schematic represents the yoking assembly:

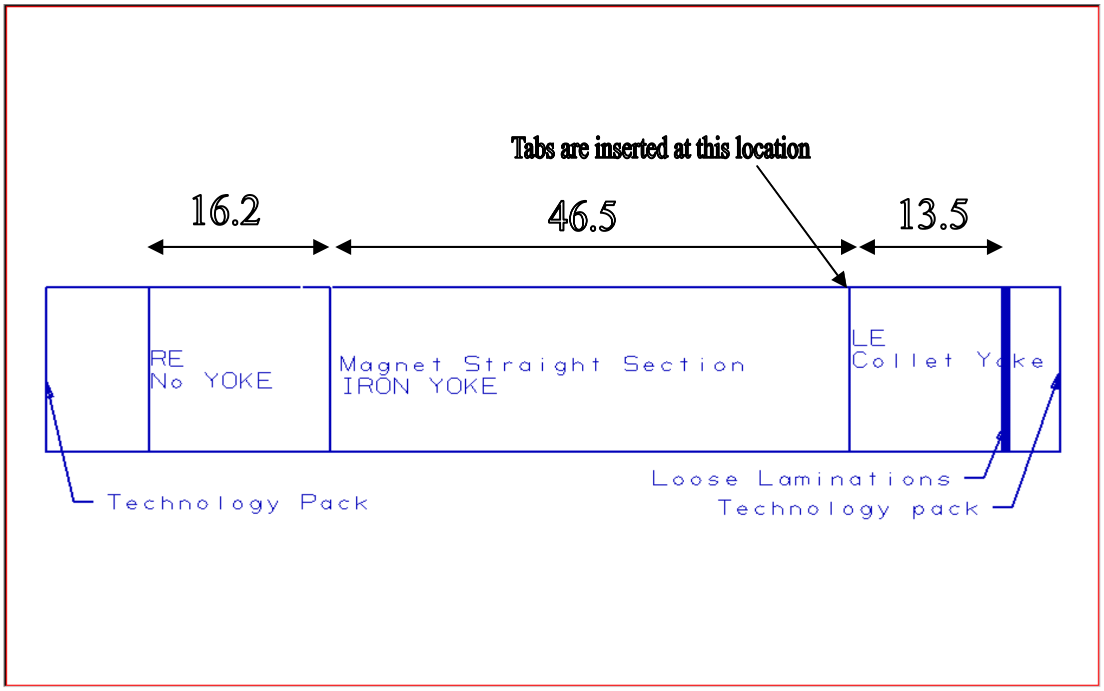


Fig. 28: *Yoking configuration for HGQ-03*

There was some concern of weld shrinkage at the RE as there is no yoke pack to support the skin. It was decided that the welding pusher displacement measurements will be made after each weld pass and will be decided on the spot when to stop welding in the RE. Note the yoke laminations were fusion welded at 7 locations (5 on outer surface and 2 on inner surface) to form packs.

The skin alignment key was 24 mm wide compared to 19 mm for HGQ-01 and 23 mm for HGQ-02. This leaves a gap of 1.75 mm between the yoke and the skin. Note for HGQ-01 there was gap of 0.75 mm between the key and the skin and the skin rests on yoke pack; for HGQ-02 the gap between the yoke and the skin was 1.25 mm. The magnet was compressed at 600 Psi during welding. The pressure seems to drop after every weld pass and so it was adjusted accordingly. For HGQ-03, there was one fusion or root pass followed by three filler passes. The last filler pass was done only upto the beginning of the RE to avoid excessive shrinkage. The distance between the top and bottom pushers was measured on both sides after each welding pass to obtain the weld shrinkage (Figs. 29 and 30). The data shows that the shrinkage pattern in HGQ03 was not symmetrical, and this may have been due to the placement of the skin alignment key flush with the return ends of the keys, such that the weld press could not continue welding as far as in previous magnets. The maximum shrinkage in HGQ-03 was 1.8 mm compared to 1.75 mm in HGQ-02 (showed some buckling of the yoke packs) and 1 mm in HGQ-01 (visible buckling). The welding process itself took about 4 hrs; a drastic improvement from 8 hrs for previous magnets and the quality of welding also seems to much better atleast visually.

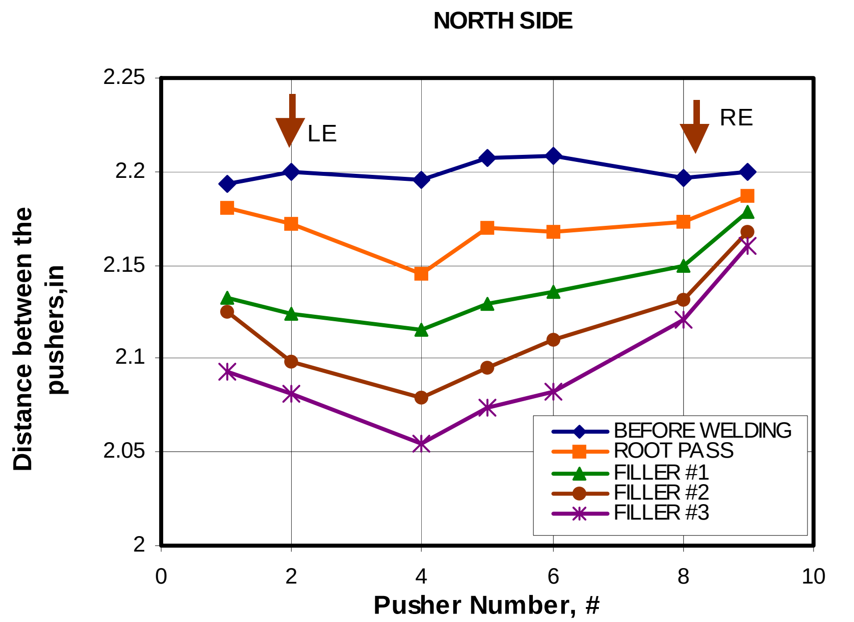


Fig. 29: *Weld shrinkage measurements on the north side of the magnet.*

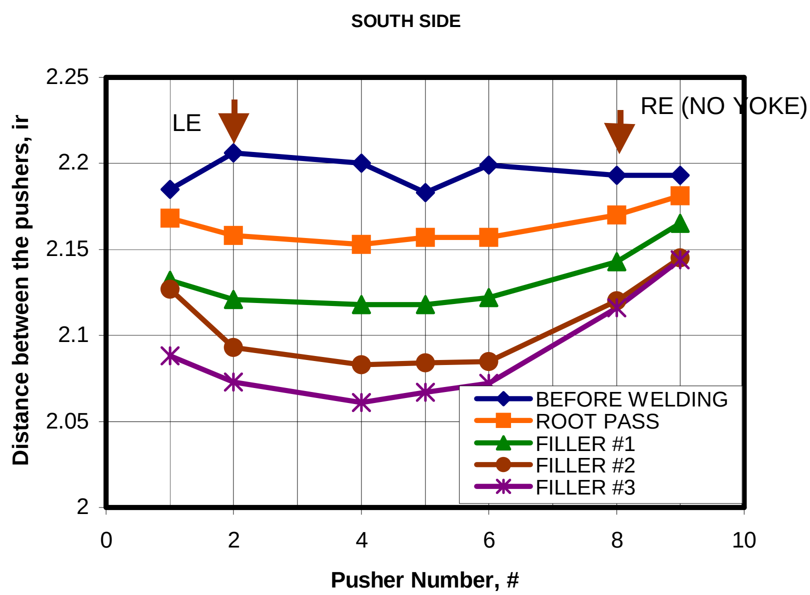


Fig. 30: *Weld shrinkage measurements on the south side of the magnet.*

The skin OD measurements using a micrometer were made along the length of the magnet at positions around the circumference at 5^0, 45^0 and 90^0. PI TAPE measurements were also made along the length of the magnet every 5 inches. The MIC measurements in the body at 5^0 position were about 4 mils over the reference diameter (16.378 inches);

however the magnet ends at his position were off by more than 0.150 inches. The measurements at 45^0 and 90^0 were very close to the reference diameter (see Fig. 31).

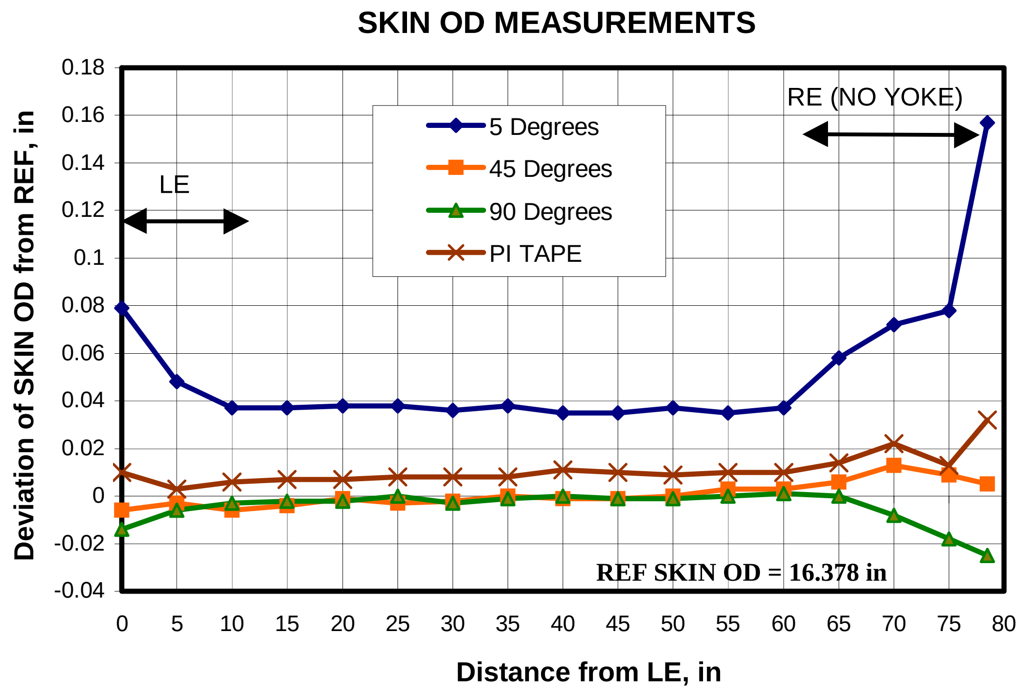


Fig. 31: *Skin OD measurements using a micrometer and a PI TAPE*

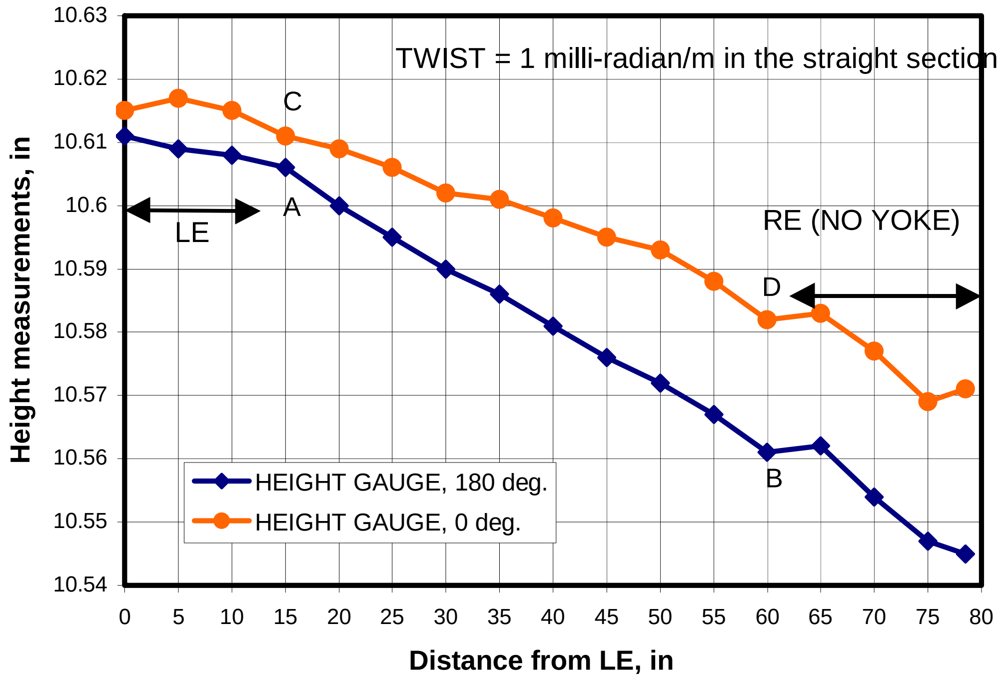


Fig. 32: *Twist measurements using a height gauge.*

The twist in the magnet was also measured using a height gauge and a twist measuring device. For the height gauge measurements, the magnet was placed on a granite table and height from the top of the table to the groove in the skin alignment key was measured along the length of the magnet. Fig. 32 shows the height gauge measurements on either side of the magnet. The twist is then computed to be 1.0 milli-radian/m in the straight section. This is slightly worst than HGQ-02 which had 0.6 milliradian/m. Fig. 33 shows the methodology used to compute the twist from height gauge measurements [*from Igor*].

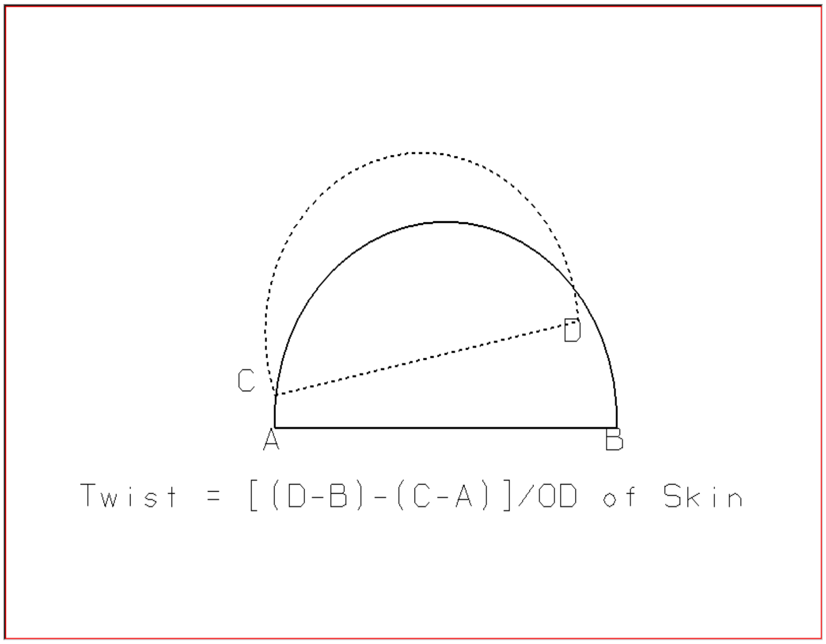


Fig. 33: *Methodology to compute twist from the height gauge measurements. The points A, B, C and D are shown in the Fig. 32*

The twist measuring device is a semicircular dome with flat top and has pivots to anchor on to the groove in the skin alignment key on either side of the magnet. An electronic level is placed on top of the flop-top and the read-out gives us directly the angular measurement (Fig. 34). The twist according to these measurements is 1.26 milli-radian per meter which agrees well with the twist measured with height gauge. (Note that the sensitivity of the electronic level used in the twist measuring device is, 1 digit = 0.01 mm/m = 2 SEC). The discrepancy reported in the previous magnets between the twist measuring device and the height gauge measurements is probably due to mistake in the conversion of the read-out on the electronic level to angle.

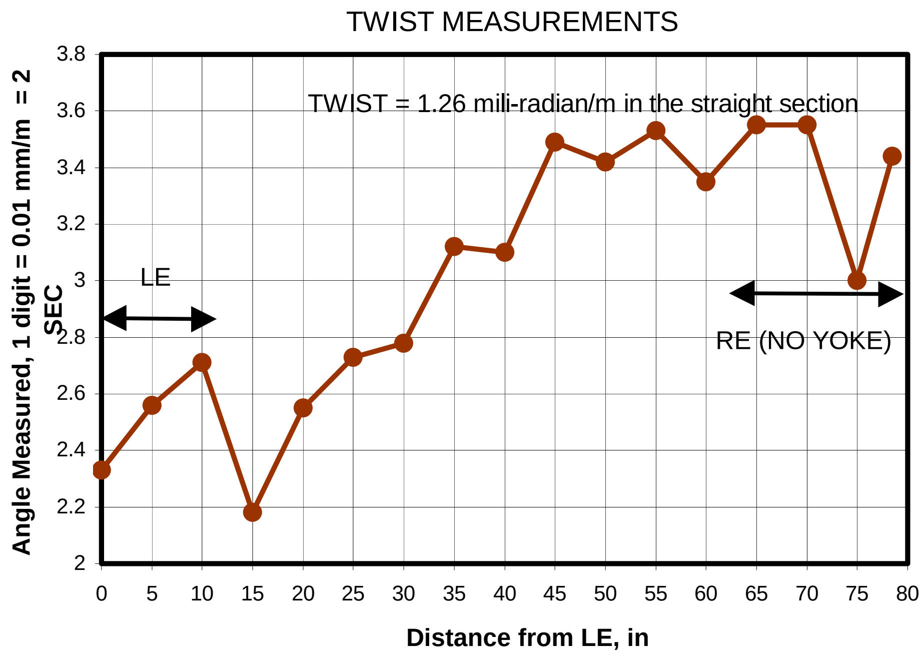


Fig. 34: *Data from twist measuring device.*

7.2 End-Plate and End-Bullets Installation

End-plates were welded on both lead and return ends. Since the skin OD close to the alignment key is about 0.15 inches bigger additional filler material had to be used while welding. Micrometer measurements were done at 5^0 location on circumference after welding the end-plate and Fig. 35 shows this data:

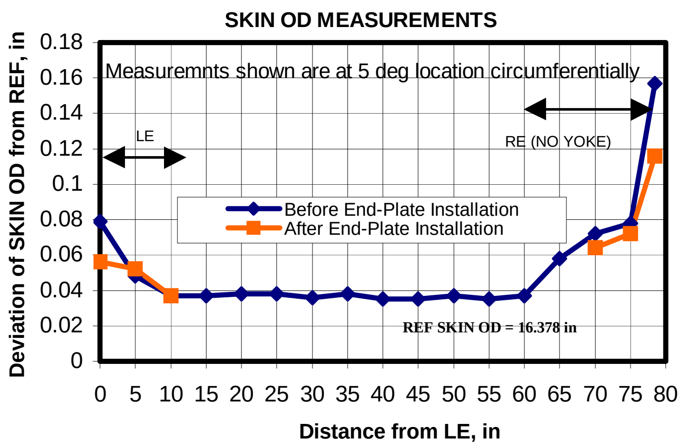


Fig. 35: *Skin OD measurements at 5^0 location before and after installing the end-plate.*

Eventhough the magnet is not going to be loaded in the ends during the first thermal cycle, end-bullets were installed if in case we decide to apply end-load during the second thermal cycle. The pressure plates were partially screwed into the outer end-saddles. This was to avoid any loading in the coils due to possible differential thermal contractions.

7.3 Testing at IB3

HGQ-03 was hi-potted coil to ground, heater to ground and heater to coil at 1500 V. Leakage is required to be less than 0.5 μA at 1500 V. All the coils and the inner strip heaters passed the hi-pot testing. However only two out of the four outer coil strip heaters tested ok. The two outer strip heaters failed (Outer Q1 and Q2 and Outer Q3 and Q4) showed leakage of 0.5 μA at around 140 V. However there is no coil to ground short. This strange behavior is yet to be explained. The adhesive used in the outer coil strip heaters to attach the kapton to the stainless steel strip flowed to certain regions. We hi-potted these regions before installing them and found the leakage to be less than 0.5 μA at 1500 V. The hi-pot data in given in Table 11.

The final electrical data collected before shipping to MTF:

	Resistance ohm	**Ls μH**	**Q**
Q1 - inner	0.0822	151.900	1.21
Q1 - outer	0.1119	283.981	1.63
Q2 - inner	0.0810	156.990	1.25
Q2 - outer	0.1120	291.899	1.73
Q3 - inner	0.0821	146.900	1.20
Q3 - outer	0.1111	283.107	1.60
Q4 - inner	0.0819	168.133	1.55
Q4 - outer	0.1125	292.680	1.74
Q1 – Quadrant total	0.1944	706.547	2.18
Q2 – Quadrant total	0.1944	740.547	2.44
Q3 – Quadrant total	0.1958	702.970	2.11
Q4 – Quadrant total	0.1957	772.603	3.05
	Resistance ohm	**Ls mH**	**Q**
Magnet Total	0.7798	4.062	2.33

Table 9: *Magnet Resistance, L and Q measurements.*

Heater	**Resistance ohm**	**Heater**	**Resistance ohm**
Q-1/2 - inner*	7.351	Q-1/2 - outer	3.916
Q-2/3 - inner	7.342	Q-2/3 - outer*	4.526
Q-3/4 - inner*	7.353	Q-3/4 - outer	3.864
Q-4/1 - inner	7.740	Q-4/1 - outer*	4.997

Table 10: *Heater resistance measurements; the heaters with asterisks were used.*

All the voltage taps were also tested and we lost 7 of them during the entire assembly process. The four inner voltage taps lost were while removing the end-can after collaring the straight section of the magnet. The following are the voltage taps lost:

Inner Coils:
- Q2 - 2A and 14A
- Q3 - 14D
- Q4 - 14B

Outer Coils:
- Q1 - 16D
- Q2 - 16B
- Q3 - 16C

<u>HGQ-03 Hipot Leakage</u> 08/5/98 R. Bossert

Measurements taken after magnet fully collared and keyed (including ends)
Taken after pulling off .500 in. of laminations to fix broken Q3 leg of Q2-Q3 outer strip heater
Requirement to pass is less than .5uA @1.5kV
Requirement for coil to coil was mistakenly taken as .5uA @100V

Q1-Q2 outer heater to coil	5uA @132V	all coils bussed together
Q2-Q3 outer heater to coil	.12uA @1.5kV	all coils bussed together
Q3-Q4 outer heater to coil	1.5uA @140V	all coils bussed together
Q4-Q1 outer heater to coil	.16uA @1.5kV	all coils bussed together
Q1-Q2 outer heater to ground	dead short	
Q2-Q3 outer heater to ground	.14uA @1.5kV	
Q3-Q4 outer heater to ground	dead short	
Q4-Q1 outer heater to ground	.12uA @1.5kV	
Inner heaters to coil (all)	<.03uA@1.5kV	all coils bussed together
Inner heaters to ground (all)	<.03uA@1.5kV	all coils bussed together
Coils to ground (all)	<.06uA@1.5kV	all coils bussed together
Coil to coil (done at 100V)		

Q1 to Q2	<.03uA @100V	Quadrants bussed together
Q2 to Q3	<.03uA @100V	Quadrants bussed together
Q3 to Q4	<.03uA @100V	Quadrants bussed together
Q4 to Q1	<.03uA @100V	Quadrants bussed together

Table 11: *Hi-Pot leakage data for HGQ-03*

8.0 Concerns

8.1 Coil Pre-Stress: Force Balance

The coil pre-stress measurements as read by beam gauges in the magnet body do not co-relate with that of the collar-coil deflection measurements and FEA. One last check is to follow the good old method of doing force balance between the main pump pressure and the coil pre-stress.

One way of doing the force balance is to assume a uniform pressure (equal to the main pump pressure) acting on a thick walled cylinder (collared coil assembly) and calculate the stress distribution using the formula (taken from Roark and Young):

$$\sigma = \frac{q\left(b^2 + r^2\right)a^2}{\left(a^2 - b^2\right)r^2}$$

Where σ = stress in the cylinder, q = uniform external pressure, a = external radius, b = internal radius and r is the radius at which stress to be determined. The maximum and minimum stress in the thick walled cylinder for a uniform external pressure of 6500 Psi is 17847 Psi or 123 MPa and 11348 Psi or 78 MPa. However according to the beam gauge measurements the coil pre-stress is around 220 MPa in the inner coils and 80 MPa in the outer coils. So the inner beam gauges read twice more than they should and outer beam gauges agree reasonably well.

The second method is to convert pump pressure to force and then calculate the reaction forces on the poles of the laminations. For each main pusher there are four surfaces at which we get reaction forces (two due to outer coils and two due to inner coils). For a pump pressure of 6500 Psi, we get a force due to single pump as 6500 Psi x 20 in^2 = 130000 lbs. The corresponding stress in the coil is then:

$$\sigma_{coil} = \frac{130000}{4 * 0.614 * 4} = 13233\,\text{Psi} = 91\,\text{MPa}$$

In the denominator of the above equation, the first *'4'* is because there are four reaction forces and the contact area = width of the cable (0.614 in) * length of the pusher block (4 in). As said before the inner beam gauges read 220 MPa and outer beam gauges read 80 MPa.

In conclusion at least the inner beam gauge readings are incorrect. The calibration data for the strain gauges was then checked and found that the data from HGQ-03 collaring is outside the range used during gauge calibration (0 - 137 MPa), suggesting a problem with the data as well. However it should be noted that the program that converts the strain gauge resistance data into pressure extrapolated linearly outside the calibration range which seems to be right. So the concern here is what to do for the next magnet and also why did this happen in HGQ-03?

8.2 Collared Coil Deflection

From the end-shape measurements with the one inch pusher block and the amount of shimming we added at the ends we can estimate the end-shape and this should some-how relate to that of the measured collar-coil deflection measurements. The following 4 figures show the estimated end-shape and size due to shimming:

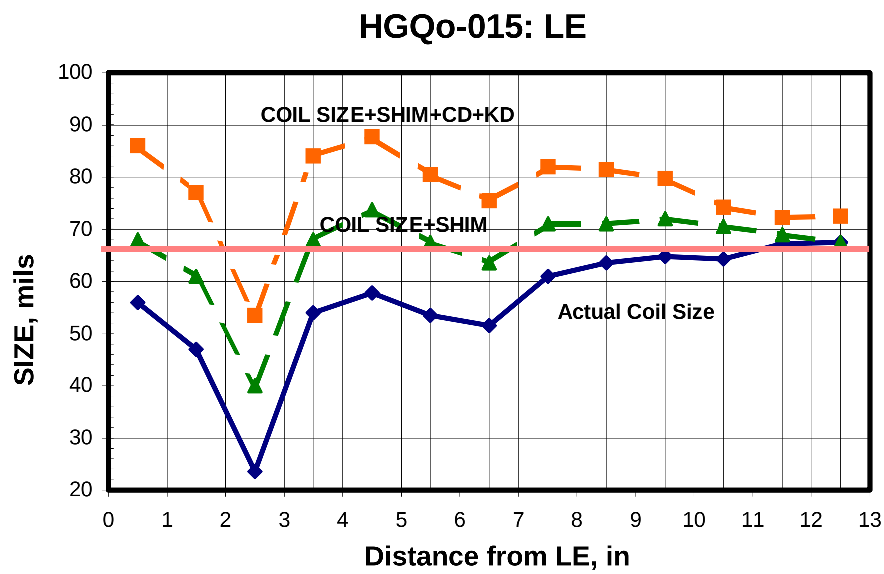
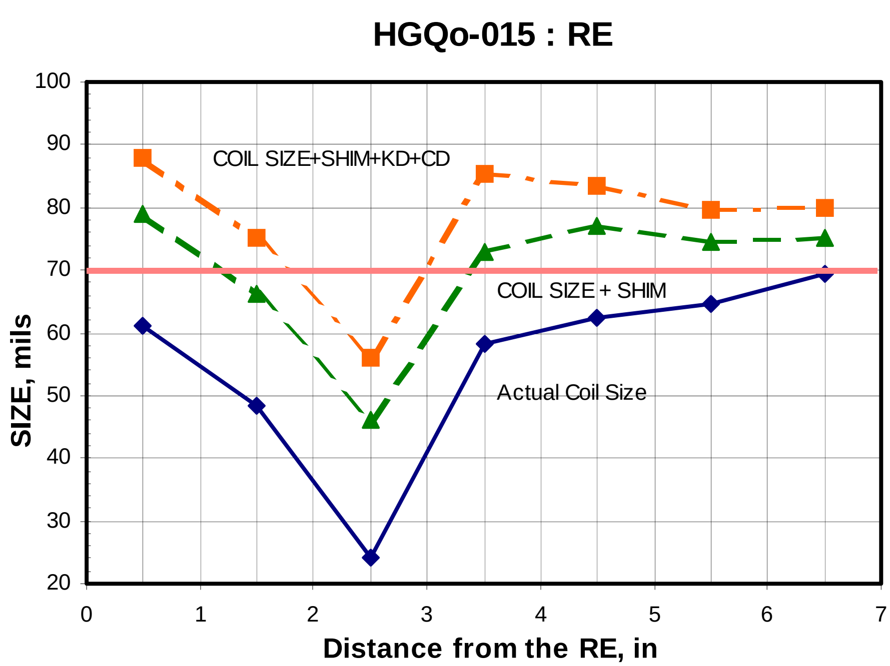


Fig. 36: *Estimated end-shape and size due to shimming for Outer LE.*



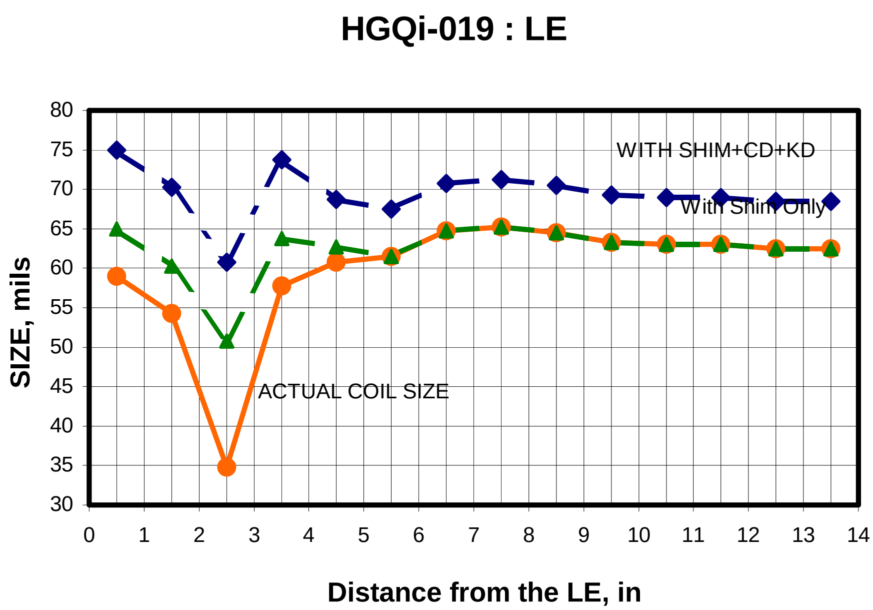


Fig. 37: *Estimated end-shape and size due shimming for Outer RE.*

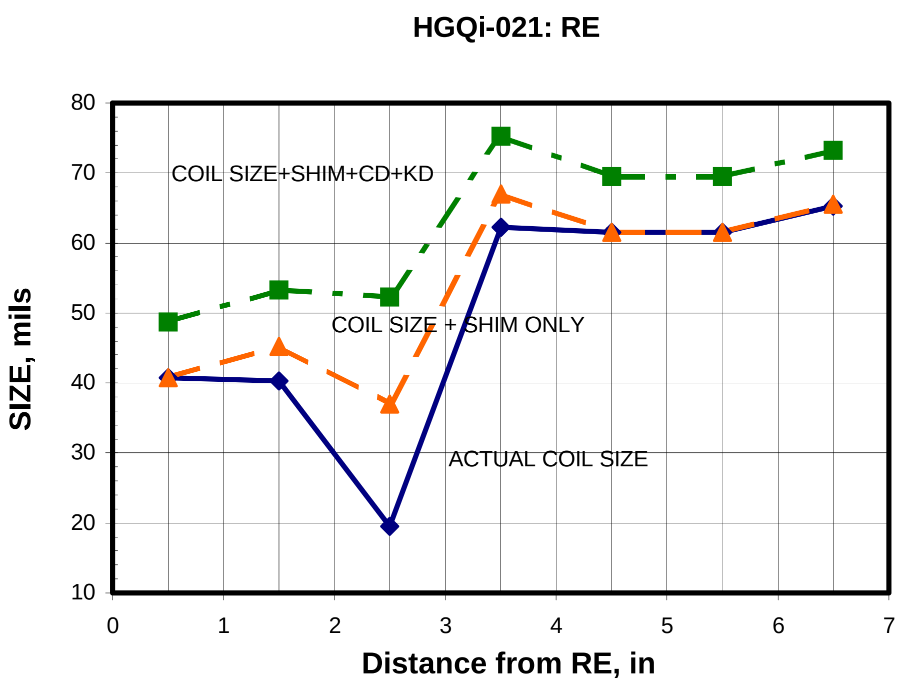


Fig. 38: *Estimated end-shape and size due to shimming for Inner LE.*
Fig. 39: *Estimated end shape and size for Inner RE*

Considering just HGQ-03, its possible to expect a drop in the pre-stress at the ends as it is clear from all the plots that even after shimming we see a drop in size. Further from Fig. 36 the end-shape with respect to the body size is similar atleast qualitatively to that of the collared coil defection measurements. But if we start to compare this magnet with that of HGQ-02, the gain in size at position #3 is only 3 mils. One thought can be that the position #3 is soft compared to the rest of the magnet and inspite of the additional shimming the spring back force could be relatively small (just a thought haven't prooved).

In conclusion, the HGQ-03 has positive pre-load throughout the length of the magnet; but the pre-stress levels at the ends are much lower than expected. So the question is what happened to the additional kapton shimming and further if HGQ-03 has poor quench performance at this location what are the alternatives?

8.3 Twist in the Magnet

There are two kinds of twist in the magnet; twist induced while collaring and keying the magnet (i.e., twist in the collared-coil assembly) and twist induced while welding the skin on to the cold mass (twist in the cold-mass assembly).

The twist in the collared-coil assembly is specific to HGQ-03 or any future internal splice magnets because the round collars used in the ends of the magnet are not properly positioned while keying. Thus measurements made in IB3 indicated that the magnet straight section is relatively free of twist and that magnet ends have considerable twist. It was later checked to see if the twist is just in the full round collars or magnets ends themselves are twisted. The result is that the magnet ends are infact twisted along with the collars. However when assembling the collared coil assembly into the yoke, a gradual twist in the whole magnet was noticed. Its possible that there is a twist in the whole magnet and that there is a change in slope at the ends. As indicated previously no attempt was made to measure the twist after putting the collared coil assembly into the yoke.

The twist in the cold-mass assembly after welding the skin was measured and found to be around 1.0 milli-radian per meter in the straight section of the magnet. The twist in HGQ-01 was 4.67 milli-radian per meter and for HGQ-02 it was 0.6 milli-radian per meter. The twist in this magnet was slightly higher than that in HGQ-02 probably because of the of no yoke in the RE. The direction of the twist is same in all the three magnets and is clockwise looking from LE to RE. The acceptable twist is however an order of magnitude less than what we have right now. So we still need to work on reducing the twist in the magnet. If we are not able to achieve our goal, we could follow BNL procedure by putting some cross-welding on the skin of the magnet to reduce twist.

8.4 ASME Code Justification

ASME requires that for a pressure vessel, we have to have a full depth penetration during the welding process. This was not achieved in HGQ-03. Shorter skins are being welded with different groove shape by A. Makaraov to see if we could get this. Once we have this design and the weld procedure, we could then work towards satisfying the intent of ASME pressure vessel code.

APPENDIX - I
SUPER CONDUCTING CABLE SPECIFICATIONS

Inner Cable Specifications

CABLE No. LHC-3-I-00**596**

CABLE LOG SHEET
LBNL-SUPERCON-AFRD
SUPERCONDUCTING MAGNET MATERIALS
BLD 52
- STRAND INFORMATION -

MANUFACTURER : IGC
BILLET # : B20360
SPOOL # : 1,2…,19
COMPOSITION : NbTi
STRAND Dia.. NOMINAL : .808 mm ***INSP. DIA..: .810 mm avg.***
Cu/SC RATIO NOMINAL : ***INSP. RATIO : na***
FILAMENT TWIST/LENGTH : 1/12.7 mm ***DIRECTION : LEFT***
SHARP BEND TEST :
LENGTH PER SPOOL : 950 m

NOTES:
-CABLING SPECIFICATION –

TYPE or SPEC.: LHC-HGQ-INNER Type#3
No. of STRANDS : 38
PITCH DIRECTION : RIGHT ***PITCH LENGTH : 114 mm***
PLANETARY RATIO : +.57:1
ROLLER ID #: P23 & P24 ***WIDTH : 15.254 mm*** ***ANGLE : 1.10deg.***
MANDREL ID #: 21 ***WIDTH : 15.15 mm*** ***THICKNESS : .60 mm***
LUBRICATION : 4BR 100% drip.
STRAND TENSION : 2.1 kg.+/-.1 kg ***TURKS HEAD LOAD "SGM": -40.0 kgm.***
Nom. THICKNESS : 1.457 mm+/-.006 mm
Nom. WIDTH : 15.400 mm+/-.025 mm
Nom. ANGLE : .99 deg. +/-0.1 deg.

- FINISHED CABLE -
FINISHED LENGTH : 882 m
Avg. THICKNESS : 1.4559 mm
Avg. WIDTH : 15.3975 mm
Avg. ANGLE : 1.048 deg.

RESIDUAL TWIST/Mtr.: 25 deg. Good direction. OK "Straightening tightens the cable"
ETCH for FILAMENT DAMAGE : OK

NOTES : Strands are "high-low" on major edge of cable and only on the top side as mfg.
Run #597 will test short length for pitch length.

4 m sample Arup Ghosh
4 m sample LBNL archive

Outer Cable Specifications

CABLE No. LHC-4-F-00**623**

CABLE LOG SHEET
LBNL-SUPERCON-AFRD
SUPERCONDUCTING MAGNET MATERIALS
BLD 52

- STRAND INFORMATION -

MANUFACTURER : Furukawa
BILLET # : : ***2-1-11003-F-07 & 11002-F-01 & 11006-F-01***
SPOOL #
COMPOSITION : ***NbTi***
STRAND Dia.. NOMINAL : ***.648 mm*** ***INSP. DIA..:*** ***.6502 mm***
Cu/SC RATIO NOMINAL : ***INSP. RATIO :***
FILAMENT TWIST/LENGTH : ***1 / cm*** ***DIRECTION :*** ***RIGHT***
SHARP BEND TEST : ***OK***
LENGTH PER SPOOL : ***890 m***

NOTES: Strand from SSC inventory at LBNL

-CABLING SPECIFICATION –

TYPE or SPEC.: ***LHC-HGQ OUTER***
No. of STRANDS : ***46***
PITCH DIRECTION : ***LEFT*** ***PITCH LENGTH :*** ***101.6 mm***
PLANETARY RATIO : ***+.57:1***
ROLLER ID #: ***P-25 & P26*** ***WIDTH :*** ***15.286 mm*** ***ANGLE :*** ***0.85 deg.***
MANDREL ID #: ***20*** ***WIDTH :*** ***14.86 mm*** ***THICKNESS :*** ***.38 mm***
LUBRICATION : ***100% 4-BR***
STRAND TENSION : ***1.7 kg*** ***TURKS HEAD LOAD “SGM”:*** ***-160 lbs***
Nom. THICKNESS : ***1.146 mm+/-.006 mm***
Nom. WIDTH : ***15.400 mm+/-.025 mm***
Nom. ANGLE : ***. 68 deg. +/-0.1 deg.***

- FINISHED CABLE -

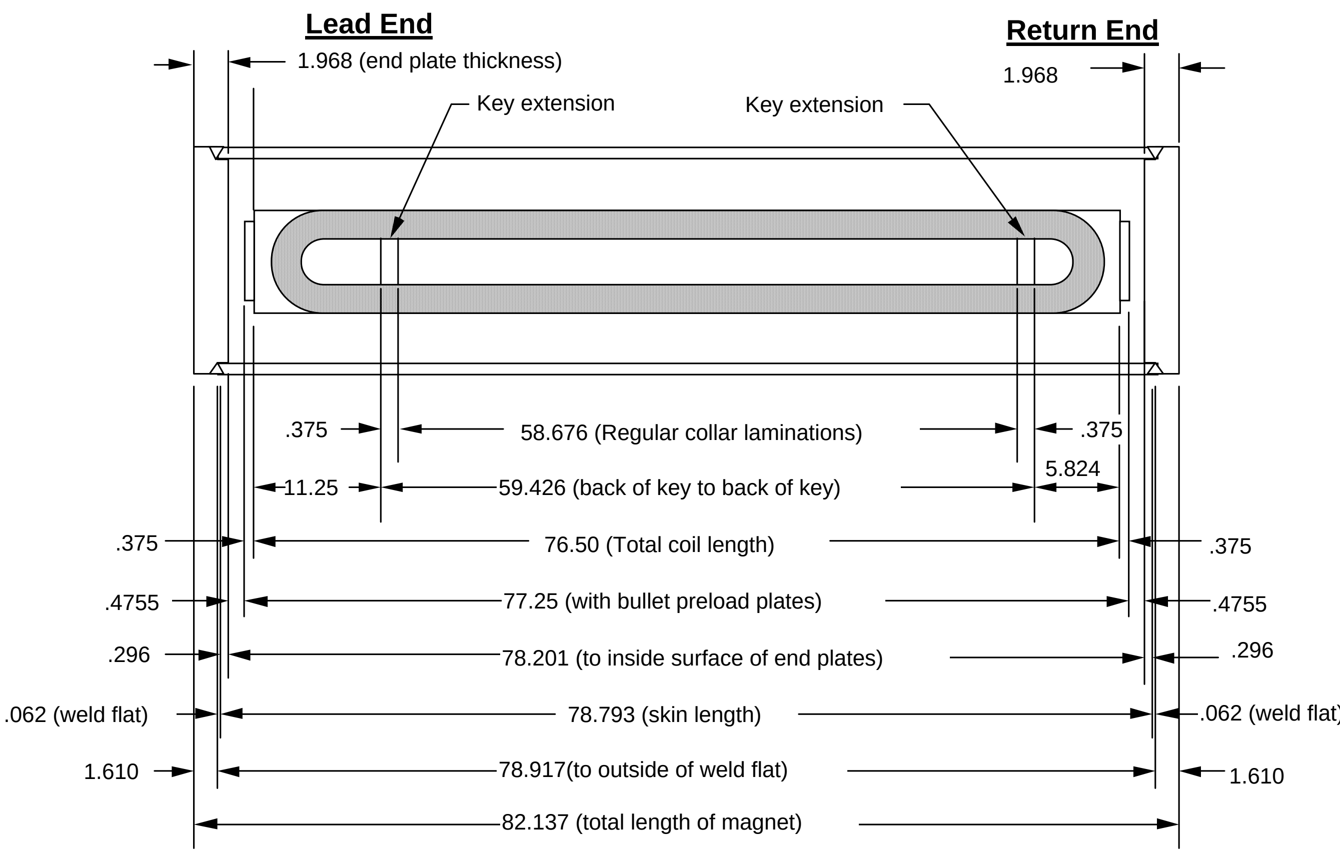
FINISHED LENGTH : ***835 m***
Avg. THICKNESS : *1.1460 mm*
Avg. WIDTH : *15.4050 mm*
Avg. ANGLE : *.703 deg.*

RESIDUAL TWIST/Mtr.: 10 deg. Under twist "good"
ETCH for FILAMENT DAMAGE : V slight random

NOTES : ***3 m for Jc Arup Ghosh***
3 m sample LBNL archive
2 cm for metallography

APPENDIX - II

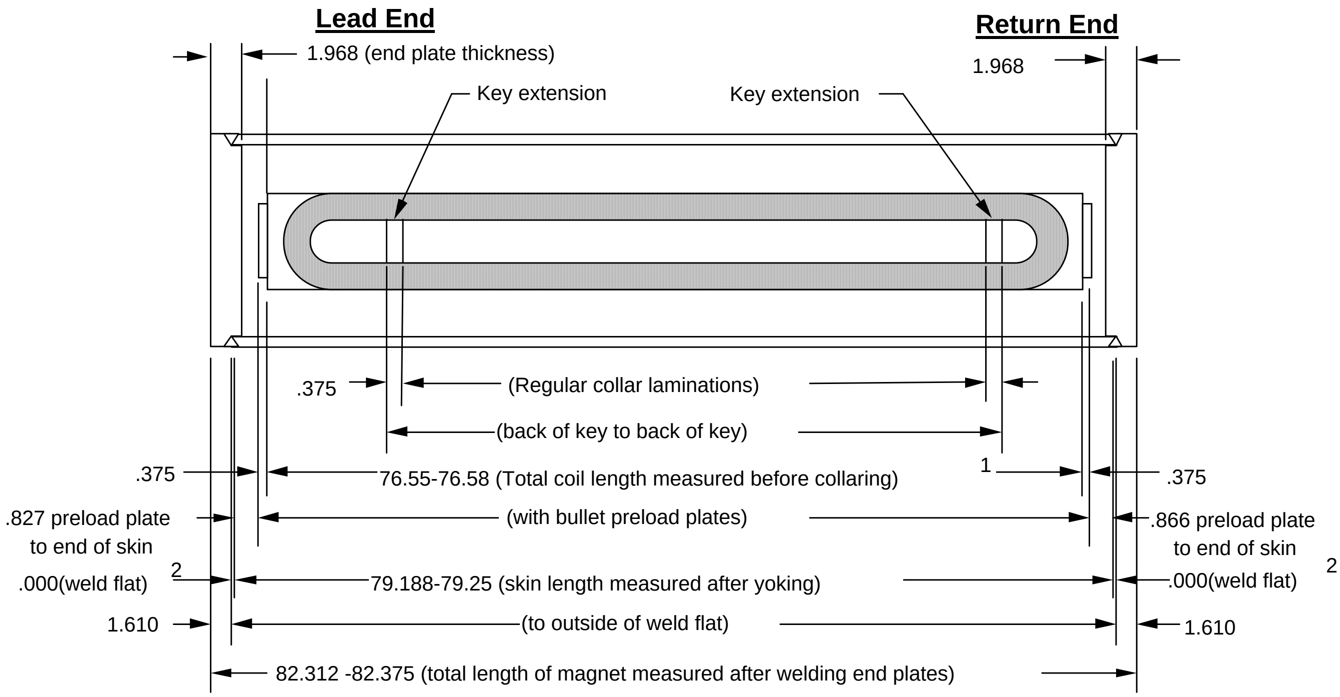
Dimensions for HGQ-03



These are the design dimensions for HGQ03

R. Bossert / D. Chichili

08/26/98



1- Coil measurements are taken before collaring. Final length after keying is longer due to lengthening during keying.

2 - Weld flat is .062 before welding but is assumed to be reduced to .000 after welding.

These are the measured dimensions of HGQ03

Measurements are not consistent, as explained below:

- Coils measured before collaring are 76.55-76.58 inches.
- Coils grow slightly in length when keyed.
- Measured skin length is 79.188-79.25.
- If all measurements are accurate, a growth of the coils due to keying of between .165 and .257 inches must be assumed.
- End plates are then welded onto skin. .062 gap is held before welding, but reduces to .000 during welding.
- Total calculated magnet length after welding end plates is then between 82.408 and 82.47 inches.
- Total measured length is 82.312-82.375 inches.
- If all measurements are accurate, a weld shrinkage of .033 - .158 inches beyond the gap closure must be assumed.

APPENDIX - III

End - Shimming for HGQ-03

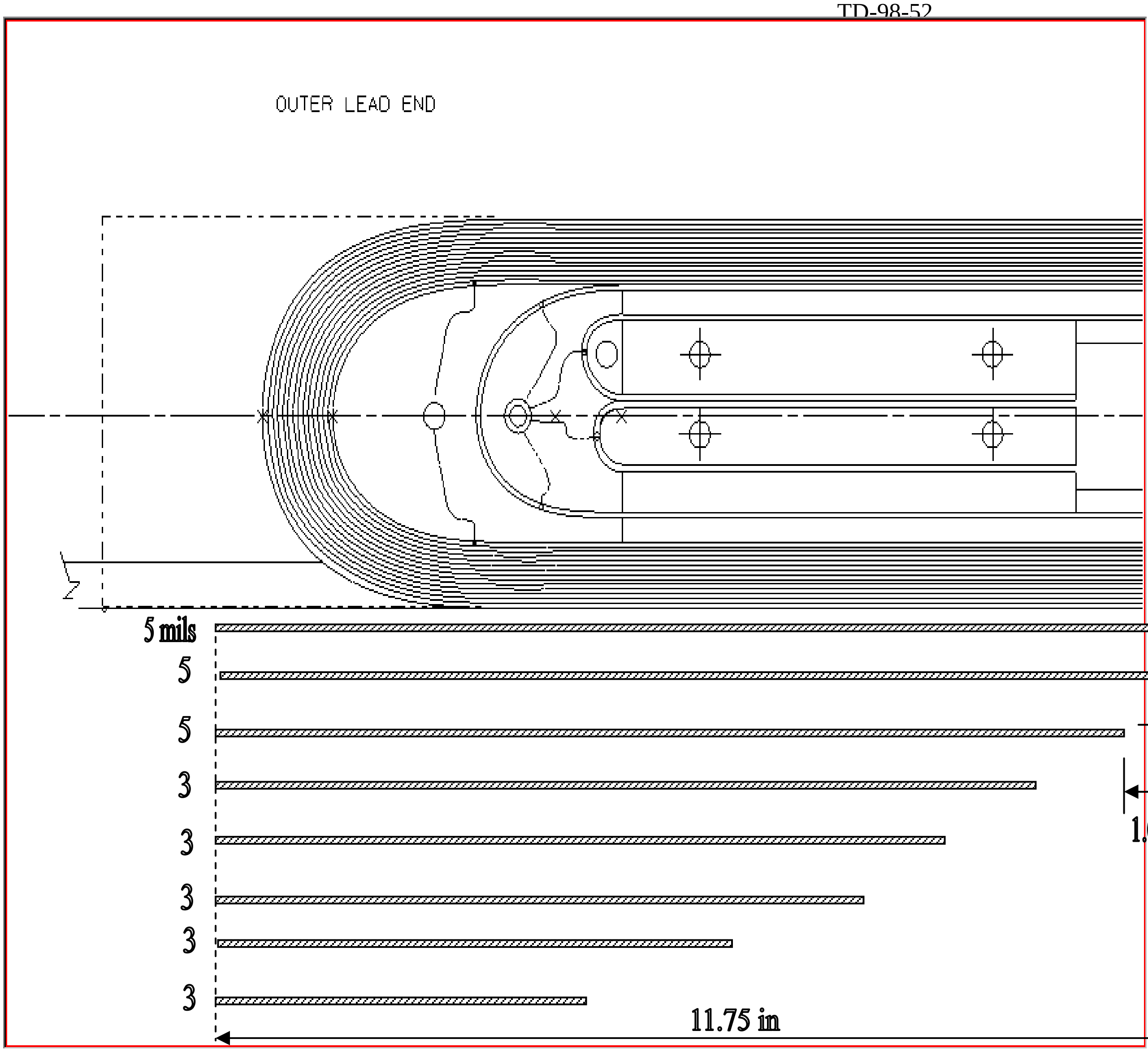
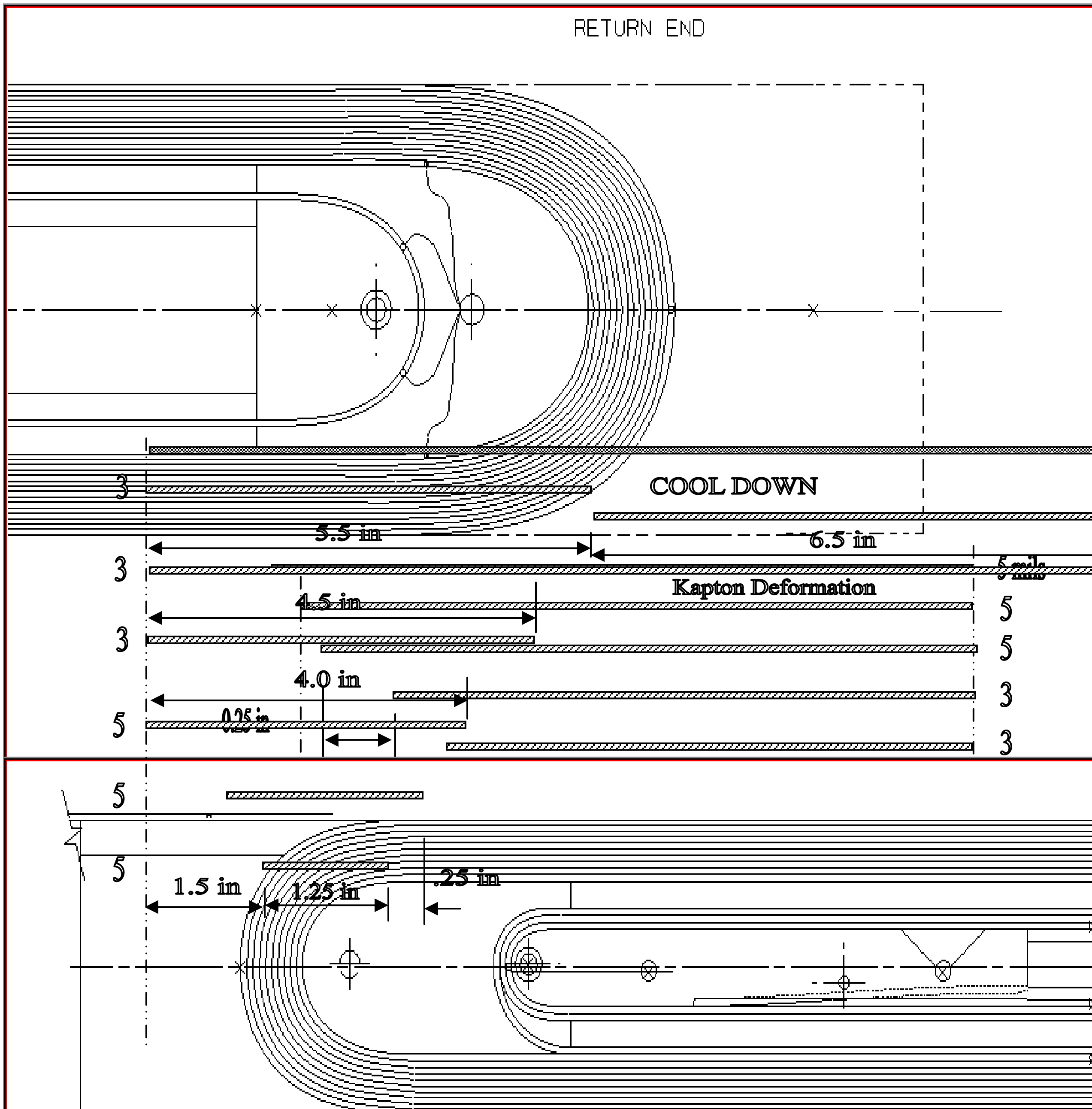


Fig. 11: *End-shimming for Outer LE.*



RETURN END
COOL DOWN
5.5 in
6.5 in
5 mils
Kapton Deformation
4.5 in
4.0 in
0.25 in
1.5 in
1.25 in
.25 in
3
3
3
5
5
5
3
3
5
5

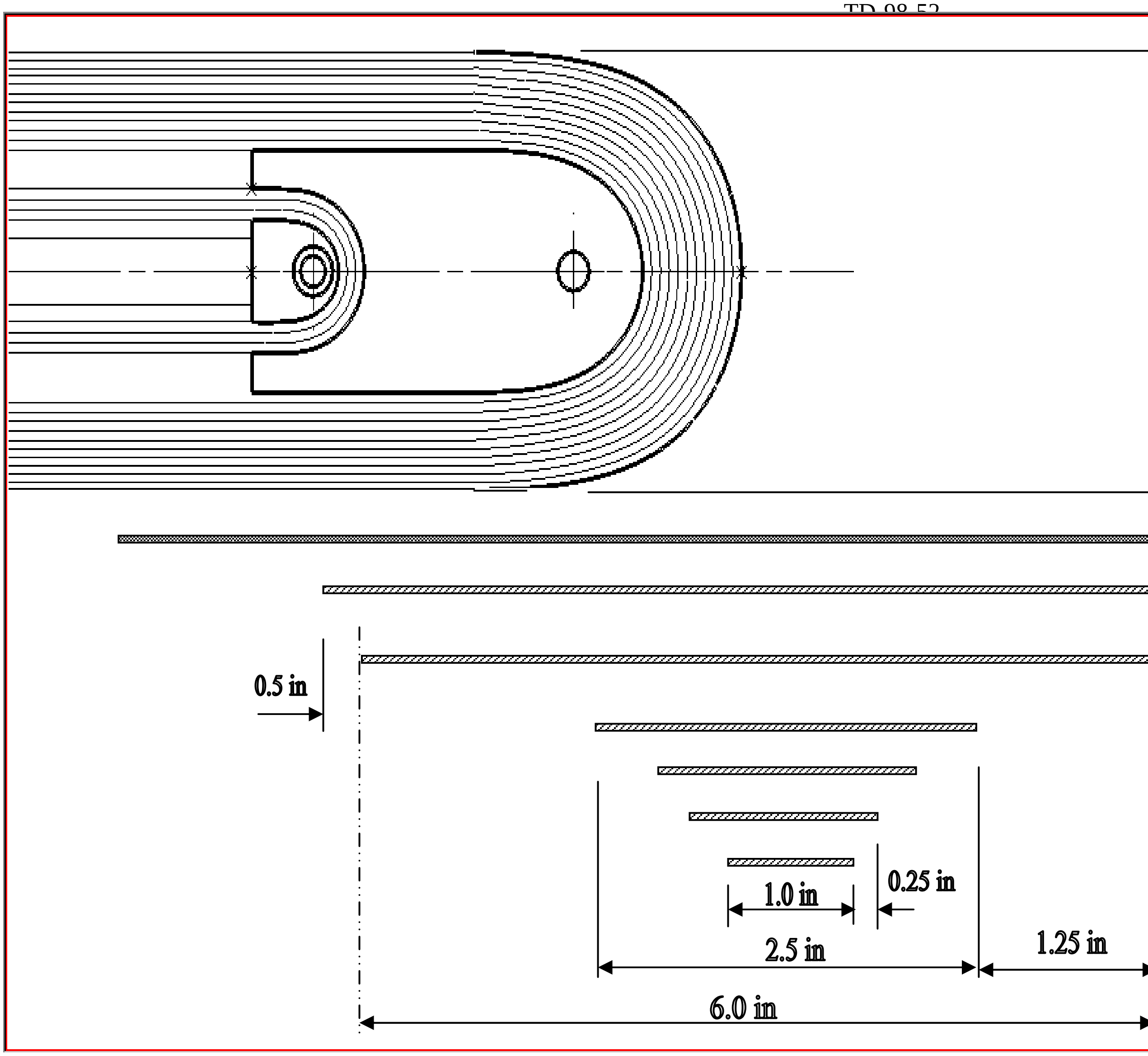


Fig. 13: *End Shimming for Inner RE*